EVOLUTION OF MLS OZONE AND THE POLAR VORTEX DURING WINTER

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Submitted to
Journal of Geophysical Research, Atmospheres
April 1994

Abstract

The evolution of polar ozone observed by the Upper Atmosphere Research Satellite Microwave Limb Sounder is described for the northern hemisphere (NH) winters of 1991/1992, 1992/1993, and 1993/1994, and the southern hemisphere (SH) winters of 1992 and 1993. Ozone in the mid-stratospheric vortex increases over the winter, with largest increases associated with stratospheric warmings, and a much larger increase in the NH than in the SH. A smaller NH increase was observed in 1993/1994, when the middle stratospheric vortex was stronger. Ozone mixing ratios decrease rapidly in the late winter SH lower stratosphere, as expected from chemical destruction due to enhanced reactive chlorine. The interplay between dynamics and chemistry is more complex in the NH lower stratosphere; however, evidence has previously been shown for chemical ozone destruction in the 1991/1992 and 1992/1993 winters. We show here evidence suggesting chemical destruction in late February and early March 1994.

The synoptic evolution in the late winter mid-stratosphere shows large tongues of high ozone drawn in from low latitudes, and tails of low ozone drawn off the vortex edge during stratospheric warmings. In the NH late winter lower stratosphere, the areal extent of high ozone values (typical of the vortex) seen in mid-latitudes depends on the strength of the lower stratospheric vortex, with the largest extent of high ozone outside the vortex in 1994, when the lower stratospheric vortex is relatively weak, and the least extent in 1993 when the lower stratospheric vortex is strongest.

Differences between NH and SH dynamics result in very different vertical distributions of high latitude ozone in the two hemispheres. In late winter, the middle and upper stratosphere contribute more to the column in the NH high latitudes than in the SH; thus lower stratospheric changes are not readily apparent in NH column ozone measurements,

Introduction

Knowledge of the evolution of ozone in the stratospheric polar vortex is crucial to understanding the chemical and dynamical mechanisms in that region, as well as diagnosing the influence of the polar regions on global ozone. Previously available ozone data are limited in vertical, latitudinal and temporal coverage, with few data available in the polar night or in the lower stratosphere.

The Microwave Limb Sounder (MLS) on board the Upper Atmosphere Research Satellite (UARS) has now measured concentrations of several species of interest in the middle atmosphere, including ozone and ClO, through three northern hemisphere (NH) and two southern hemisphere (SH) winters. MLS measurements extend throughout the stratosphere and include the polar night. They provide unprecedented coverage of the winter polar regions, including the vertical distribution of ozone and both northern and southern polar regions. The only similar data are from LIMS, but they cover only one NH winter. Froidevaux et al. [1994a, submitted to *J. Atmos. Sci.*] describe the general features of MLS ozone, focusing on the zonal mean; Elson et al. [1994, submitted to *J. Atmos. Sci.*] show corresponding observations of planetary scale waves in ozone. Waters et al. [1993a] show the evolution of vortex averaged ozone in the Arctic lower stratosphere during the 1991/1992 winter, and Manney et al. [1993] and Waters et al. [1993b] report on some aspects of ozone evolution in the 1992 Antarctic late winter. Manney et al. [1994a] show the evolution of ozone in the NH lower stratosphere in late winter 1993.

In the following, we describe the distribution and evolution of ozone during winter (December through March in the NH and June through September in the SH) in relation to the structure and evolution of the stratospheric polar vortex, for each of the winters with MLS observations. We focus on the vertical distribution and comparisons between the winters. We also show the evolution of synoptic features during late winter in both hemispheres, Differences in the distributions in the two hemispheres and possible implications for the dynamical and chemical processes that affect ozone are discussed

Data and Analysis

"The MLS ozone data are from the 205 GHz radiometer; they have horizontal resolution of ≈400 km and vertical resolution of ≈4 km; however, current retrievals are performed on a vertical grid with ≈6 km spacing [Froidevaux et al. 1994, submitted to *J. Atmos. Sci.*]. The measurement technique is described by Waters [1993] and the UARS MLS instrument by Barath et al. [1993]. Retrieval methods are summarized by Froidevaux et al. [1994, paper in preparation]. Precision (rms) of individual ozone measurements from 50 hPa to 1 hPa are ≈0.3 ppmv, with absolute accuracies of ≈5-- 10% in the middle and upper stratosphere, and =10--30% in the lower stratosphere [Froidevaux et al. 1994, submitted to *J. Atmos. Sci.*]. The ozone data used here are gridded using Fourier transform techniques that separate time and longitude variations [Elson and Froidevaux 1993].

The Rossby-Ertel potential vorticity (PV) is used to describe the polar vortex. The meteorological data used in conjunction with the MLS data are analyses from the United Kingdom Meteorological Office (UKMO) assimilation system [Swinbank and O'Neill, 1994]. The UKMO analyses are currently based on NOAA operation] sounders and do not as yet include assimilation of UARS data. Winds and temperatures are used to calculate PV employing the algorithm described by Manney and Zurek [1993]. Since MLS temperatures are currently available only for pressures ≤ 22 hPa, UKMO temperatures are used to interpolate gridded MLS ozone to isentropic (potential temperature, θ) surfaces. PV is scaled in "vorticity units" , where it is divided by a standard atmosphere value of the static stability [Manney and Zurek 1993; Dunker ton and Delisi 1986], for examination of vertical sections. With this scaling, PV on isentropic surfaces throughout the stratosphere has a similar range of values.

MLS data are now available for the 1991/1992, 1992/1993, and 1993/1 994 winters in the NH, and 1992 and 1993 winters in the SH, Because of the UARS orbit, the MLS instrument switches from viewing $\approx 34^{O}$S to 80^{O}N to viewing $\approx 80^{O}$S to 34^{O}N approximately every 36 days. This observational pattern provides north-looking observations during December and early January and mid-February to mid-March; and south-looking observations *during* June and early July, and mid-August to mid-September. A summary of the observational coverage for winter high latitudes is given in Table 1, with dates noted when MIS data are missing or incomplete. Days when sufficient data were missing that the Fourier-transform gridding procedure was not reliable can be seen as blank spaces in the time series shown (Figures 5 and 6).

Time Evolution of Ozone and the Polar Vortex

Figure 1 shows time-mean, zonal-mean plots of ozone as a function of latitude and pressure for each of the early and late winter periods examined, and plots of the difference between the corresponding early and late winter time mean fields. Each time-average is for 30 consecutive days, so those for Jun/Jul 1992, Dec 1993 and Feb/Mar 1994, when there are missing data, include less than 30 days of data (Table 1). A number of features are apparent in the mid- and high-latitude ozone distributions that are similar to climatological ozone from SBUV shown by Nagatani et al. [1988] (although SBUV data do not cover the polar night or the lower stratosphere). In early winter, the level of maximum ozone mixing ratio tilts upward toward the pole, an effect which is much more pronounced in the SH than the NH. This feature has previously been noted in other ozone data [e.g., Dutsch 1974, Wu et al, 1985], in the data shown here, and in the SBUV climatology, the ozone mixing ratio at high latitudes peaks at ≈ 5 hPa in the NH (slightly higher in Dec 1993), and ≈ 2 hPa in the SH. in Dec 1991 and Dec 1992, this upward shift with latitude of the ozone maximum is less pronounced than in Dec 1993 and in the

SB JV climatology. Manney et al. [1994c, submitted to *Q. J. Roy. Meteor.* Sot.] showed tha minor warm ings in NH early winter 1993 had less influence on the upper stratosphere than in the NH 1991 and 1992 early winters; the qualitative differences in the 1993 early winter zonal mean from the 199 I and 1992 fields suggest that transport associated with these events is instrumental in dete rmining the, early winter ozone distribution in the middle and upper stratosphere. The upward tilt with latitude results from a combination of photochemical and vertical transport processes [Perliski and London 1989] and has been reproduced in a number of two-dimensional mode] calculations [e.g., Ko et al. 1984, Tung and Yang 1988, Yang et al. 199 1]. in the SH during early winter, there is a shoulder apparent below 10 hPa near 50-600 latitude, which also appears, but is not as pronounced, in the SBUV climatology and in the N} I in Dec 1993. This feature has also been reproduced in two-d imensional model simulations [e.g., Tung and Yang 1988].

During late winter, the upward altitude shift with latitude of the ozone peak is less pronounced than during early winter, particularly in the SH. For each period, the high latitude ozone peak in late winter is between 5 hPa and 3 hPa. in the NH in 1991/1 992 and 1992/1 993, ozone at high latitudes is greater in late winter than in December at all altitudes above the ≈50 hPa pressure. level. In contrast, in the N} 1 in 1993/1994, and in the S11, mid-stratospheric ozone is greater in late winter below the altitude of the ozone mixing ratio peak, and smaller in late winter above. This pattern of differences is due to the relatively high altitude of the ozone peak in early winter in the SH and in the NH in 1993/ 1994, and to the lack of strong warming events, with their associated increase in upper stratospheric ozone, in midwinter in each of these time periods, in these important respects, the N] 1 middle and upper stratosphere in 1993/1 994 winter resembles the SH winters more strongly than it does the previous two NH winters. The decrease above the ozone peak in the N]-] in 1993/1 994 and in the SH winters shows that downward transport (which decreases ozone above the peak) dominates poleward transport (which increases high latitude ozone) in the upper stratosphere for these. winters.

In the SH lower stratosphere, the formation of the "ozone hole" is apparent in the large high latitude decrease between early and late winter; this decrease continues into early spring. Although chemical depletion occurred in the NH lower stratosphere in Feb/Mar 1993 [Manney et al. 1994a] only a very slight decrease is seen below ≈50 hPa between early and late winter in the difference plot. Several factors contribute to the lack of an obvious decrease here, namely: 1) the NH decrease is smaller than in the SH, 2) most of the decrease occurs between mid-February and mid-March so it is washed out in the time mean, and 3) the zonal mean is less representative of the flow in the NH so vortex and extra-vortex values are averaged together [e.g., Manney et al. 1994a].

Figure 2 shows another view of the average early winter and late winter ozone distributions. Time mean ozone mixing ratios are plotted as a function of scaled PV and θ, with ozone averaged around a PV contour. The time periods covered are the same as in Fig. 1. Although the relationship between PV and a chemical tracer changes over the 30 day averaging period due to diabatic and other non-conservative processes [e.g., Butchart and Remsberg 1986; Haynes and McIntyre 1987], this type of average approximately separates vortex and extra-vortex values, whereas a zonal mean typically does not, The comparison between early and late winter distributions indicates the overall type of changes that occur in (he relationship between PV and ozone mixing ratio. Changes in the vertical distribution of omne appear similar to those in Fig. 1 when viewed with respect to θ. In 1991/1992 and 1992/1993 in the NH, higher ozone values are seen at a given PV in the late winter mid-stratosphere than in early winter, whereas in 1993/1994, and in the SH, lower ozone values are seen at a given PV in the late winter mid-stratosphere.

The development of the general distributions and relationships shown in Fig. 1 and Fig. 2 is examined below using the available data to show the day-to-day evolution of ozone and its relationship to the evolution of the polar vortex for each winter.

Figures 3 and 4 give an overview of the evolution of the polar vortex throughout each winter. Area integrals of PV [Butchart and Remsberg 1986] derived from the UKMO analyses are shown in Fig. 3 for December (June) through March (September) in the NH (SH), at 840 K (near 10 hPa, in the middle stratosphere) and 465 K (near 50 hPa, in the lower stratosphere). Figure 4 shows time series as a function of θ of minimum daily temperatures in the region inside the $1.4 \times 10^{-4} s^{-1}$ scaled PV contour (bold contour in Fig. 3). Strong stratospheric warmings are common in the NH winter. In 1992, there was a nearly-major warming in mid-January [Naujokat et al. 1992, Manney and Zurek 1993]. in 1993, two strong warmings occurred in mid-February and early March [Manney et al. 1994b]. In 1994, there was a virtually-major warming at the end of Dec 1993/beginning of Jan 1994. These events are apparent in the 840 K plots of the vortex, when contours of PV in the region of strong gradients (indicating the edge of the vortex) begin to spread out, and the area within them shrinks; the approximate times of the peaks of significant warming events are indicated in Fig. 3. In addition, during the strongest warmings, and during the NH final warming, the region of strong PV gradients may shift so that PV contours that were toward the low PV side. of this region are outside of it (e.g., March 1992 in Fig. 3). The warmings are apparent in Fig. 4 as an increase in minimum temperatures or a steepening of an already increasing temperature trend. After the warming in late January 1992, the mid-stratospheric vortex remains weaker and smaller through the remainder of the winter, until the final warming in late March. In 1993, the late warmings in February and early March lead directly into the final warming. In contrast, the vortex in 1994 recovers considerably after the strong warming in early January, and no more strong warmings occur until the beginning of the final warming in late March; PV gradients in the mid-stratosphere remain strong much later than in 1992 or 1993, reminiscent of the S1-1. The mid-stratospheric vortex in the SH is considerably stronger and larger than the NH vortex, anti there is little impact of strong wave activity before the end of August. in 1992, there are several minor warmings in late August/early

September [Fishbein et al. 1993, Manney et al. 1993], and strong wave activity continues to erode the vortex after this time. in 1993, the vortex remains strong throughout the period shown, with one warming event noticeable in late August. Minor warmings in earl y winter {i.e., Nov/Dec (May/Jun) in the NH (SH) } are common in both hemispheres [Manney et al. 1994c, submitted m Q. *J.* Roy. *Meteor.* Sot.], although they have little impact on the development of the SH polar vortex. The approximate times of the largest early winter warmings are also indicated on Fig. 3.

At 465 K, in the lower stratosphere, the effect of stratospheric warm ings on the vortex evolution in the NH can again be seen in a weakening of the strong PV gradients and decrease in the area enclosed by the contours. This occurs later than the corresponding" change in the mid-stratosphere. Again, as is well known, the vortex is larger and stronger in the SH; stratospheric warmings there are weaker and generally confined to higher altitudes [e.g., Fishbein et al. 1993], so their effect is not apparent at this level. The strong warmings in mid-winter and late winter in the NH are usually sufficient to raise lower stratospheric temperatures above the PSC formation threshold, while SH lower stratospheric temperatures remain well below this threshold throughout the winter (Fig. 4). overall, NH lower stratospheric temperatures were lowest and most persistently low in 1993 and highest in 1994 until late February. Consistent with this, the lower stratospheric vortex in 1993/1994 is slightly weaker than in 1991/1992, and much weaker than in 1992/ 1993 (Fig. 3). In late February 1994, the lower stratospheric vortex strengthens, and temperatures decrease below the PSC formation threshold for an approximately two week period.

Figure 5 shows a view of the time evolution of MLS ozone as a function of height in each early and late winter high-latitude viewing period, An area-weighted average of ozone at locations with scaled PV greater than 1.4 x $10^{-4} s^{-1}$ (this PV contour is indicated in Figs. 2 and 3) is shown. Plots of renal mean MLS ozone as a function of time and latitude throughout the stratosphere are shown by Froidevaux et al. [1 994, submitted to *J. Atmos. Sci.*]. The PV contour chosen is always in the region of strong PV gradients for tile.se periods, although in the N] I mid-stratosphere it is near the the outside of this region (Fig. 3). It thus serves as a guide for averaging over ozone that is generally within the polar vortex. The genera] features of the average shown in Fig. 5 are not highly sensitive to the exact PV contour used for the average, as long as it is in the region of strong PV gradients.

in the middle and upper stratosphere ($\theta > 69$(I K, and especially near the level of the ozone mixing ratio peak) the trend is for vortex ozone to decrease slightly in early winter in the NH, and in early-to-mid winter in the SH. This decrease is terminated by an overall, but episodic increase in mid-to-late winter which by the final warming in the NH produces the highest ozone mixing ratios for the year in the polar regions, In the SH, the final warming is much later (mid-November in both 1992 and 1993); by the end of the period shown here, peak ozone mixing ratios are already comparable to the values at the beginning of the early winter period. The timing, intensity, and persistence of warming events are critical to the detailed features seen in individual years.

The NH early winter 1992/1 993 vortex was relatively strong and not much disrupted by warmings, and the decrease in area-averaged ozone in the upper stratosphere was apparent in early December and persisted through the early winter period (Fig. 5). Early winter ozone decreases in 1991/1992 and 1993/1994 are apparent] y temporaril y reversed by minor warmings in December which more strongly affected the vortex. The general increase in the NH began earliest in 199 1/1 992, coincident with the strong warming in early to mid-January 1992 that significantly eroded the vortex. Ozone in early February 1994, when MLS resumed looking north in that year, is higher than it was in early January 1994. This suggests that the virtually-major warming at the end of December 1993/beginning of January 1994 may have produced a significant increase in vortex ozone.

In the NH late winter, strong warming events are accompanied by a sharp increase in the area-averaged (vortex) ozone mixing ratios in the middle and upper stratosphere. in March 1992 the vortex is already weak as the final warming begins, and ozone increases gradually. Rapid ozone increases are seen at the time of stratospheric warmings in February and early March 1993. In 1994, no strong warmings occur after early January, and vortex ozone does not increase substantially until the beginning of the final warming in mid-March.

in the SH, the decrease in vortex ozone near the mixing ratio peak in early winter 1992 resembles that in the NH in December 1991 and 1993. However, the increase in vortex ozone is smaller and occurs much later, consistent with the presence of a strong PV barrier throughout the period considered here. Ozone increases begin in early September, when minor warmings begin to significantly weaken the polar vortex. The major decrease in 1993 SH vortex ozone was in mid-winter, when MLS was looking north. An ozone increase in the middle and upper stratosphere in late August is transient, associated with an isolated warming at that time, which weakens the vortex only temporarily. The weakening of the 1992 SH vortex in early September suggests that more poleward transport is likely in the 1992 SH late winter than in 1993. This is consistent with calculations of air motion for these two winters [Manney et al., 1994d, submitted to *J. Atmos. Sci.*]. Time-series of zonal-mean ozone [Froidevaux et al., 1994, submitted to *J. Atmos. Sci.*] indicate similar increases in high latitude ozone in the mid-stratosphere.

The above picture is consistent with the early decline in vortex ozone in the middle and upper stratosphere being due to seasonally developing downwelling and differences in the effects of diabatic cooling on the distributions of PV and ozone, and with the increases being due to horizontal transport of ozone during stratospheric warmings. The effect of downwelling is to lower the level of the ozone peak, and reduce peak mixing ratios by broadening of the peak or by horizontal divergence. Diabatic effects can alter the relationship of ozone to PV in other ways as well [e.g., Butchart and Remsberg 986, Haynes and McIntyre 1987], so that changes in PV may also alter the area-average within a PV contour. Warming events which significantly perturb the zone of strong PV gradients are much more frequent and persistent in the NH than in the SH, and the strongest events are usually in the NH late winter. While the early winter ozone mixing ratio peak is at higher θ in the SH, and in December 1993 in the NH, by late winter the peak moves down to comparable levels in all five winters. This descent is particularly rapid during late December 1993/early January 1994, consistent with enhanced diabatic descent during the strong stratospheric warming at that time.

One striking difference between the NH and SH is the vertical variation of vortex ozone in early winter at levels below the ozone peak. Below about 700 K the vertical gradient of ozone in the SH vortex is small in early winter, particularly in 1993. in the NH vertical gradients of vortex ozone are remarkably similar in the three years below about 700 K in early winter, and are much stronger than those in the SH. Early winter SH vertical ozone gradients are much stronger than in the NH between about 700 K and 900 K.

Ozone in the lower stratosphere shows little trend in the NH vortex area over the December/early January time period, in the SH early winter, in late June 1992, ozone decreases slightly between ≈550 and 600 K; Manney et al. [1994e, submitted to *J. Atmos. Sci.*] suggest that this is likely due to chemical loss, as it appears inconsistent with the results of transport calculations. A similar, but even smaller, decrease is seen near these levels in 1993.

Between early July and mid-August in the SH, ozone throughout the lower stratosphere decreases substantially; Waters et al, [1993b] show that enhanced chlorine monoxide was seen throughout the sunlit part of the vortex by early July 1992, so chemical depletion of ozone would be expected. in the NH, slight decreases are seen between early January and mid-February in 1992 and 1993 below ≈500 K; a slight increase is seen in 1994. Enhanced ClO was seen in the NH in early January 1992 [Waters et al. 1993a] and from middle to late February 1993 [Manney et al, 1994a]; in 994, little enhancement of ClO was seen in either early January or mid-February, consistent with warmer lower stratospheric temperatures at this time [Waters et al. 1994, paper in preparation], Since dynamical effects would generally be expected to increase ozone in the lower stratosphere at this time, especially in January 1992, when there was a strong stratospheric warming [e. g., Manney et al. 1994a], the slight decreases in 1992 and 1993 between early and late winter are suggestive of chemical 10SS.

By mid-February 1992, MLS observed a significant decrease in enhanced ClO from values observed in January 1992, and lower stratospheric C1O continued to decrease through the late winter. NH lower stratospheric vortex ozone increases slight] y in February and March, consistent with dynamical effects [Manney et al. 1994a]. Manney et al. [1994a] showed that the decrease in NH vortex-averaged lower stratospheric ozone between mid Feb and mid-Mar 1993 was not consistent with dynamical effects, and elevated ClO values at this time indicate chemical depletion. Manney et al. [1994e, submitted to *J. A tmos. Sci.*] showed that transport processes would have caused ozone to increase significantly at this time, suggesting that chemical processes are responsible for ozone destruction greater than the observed decrease in ozone.

Lower stratospheric ozone in the SH late winter decreases rapidly from mid-August to mid-Septem her. At 465 K in the SH in both 1992 and 1993, MLS observed enhanced C1O persisting through at least the end of its south-looking period [Waters et al. 1993a,b; Waters et al. 1994, paper in preparation]. 'l'he steep decrease in lower stratospheric ozone during August and September is consistent with chemical destruction being the dominant mechanism for changing ozone at this time. The vortex averaged ozone at ≈465 K is higher during early winter in 1993 than 1992, but lower during late winter, During late winter, the rate of ozone decrease is nearly identical in the, two winters. Vortex-: -averaged C1O at 465 K was slightly higher at the beginning of the Aug/Sep period in 1993 than 1992, and decreases more slowly over the time period [Waters et al., paper in preparation], consistent with the slower increase in lower stratospheric temperatures (Fig. 4).

The contrast in the distribution of ozone in the northern and southern hemispheres is striking, and reflects the differences in the polar vortex in the two hemispheres. Because there is much stronger wave activity in the NH, and the vortex is weaker, ozone in the NH middle and upper stratospheric vortex increases much mm-e rapidly in late winter. In the 1993/1 994 NH winter, there was considerably less wave activity in the mid-stratosphere during middle and late winter than in the other two NH winters. As a result of this, and of an early winter ozone distribution already more similar to the S} I, the mid-stratospheric ozone distribution during the 1993/1 994 NH winter bears a stronger resemblance to that in the SH winters, as was seen in Figs. l and 2. In the lower stratosphere, the more disturbed NH conditions give rise to higher temperatures (Fig. 4) and thus considerably less time when conditions are such that PSCS can form and lead to ozone destruction via chlorine chemistry. The result is a pattern of ozone in the lower stratosphere that is usually dominated by dynamics in the NH and one that is dominated by chemistry in the SH.

Differences in the vertical distribution of ozone have a profound effect on the trends in column ozone. Froidevaux et al. [1994, submitted to *J. A tmos. Sci.*] show that, although lower stratospheric ozone is decreasing in Feb and March 1993, column ozone is increasing in high latitudes; in contrast, the column ozone decreases rapidly in late winter in the SH, the well-known "ozone hole". In Figure 6, we examine the distribution of ozone mass in the polar vortex in the two hemispheres. The mass of ozone in the polar vortex is calculated for layers throughout the stratosphere as described by M anney et al. [1993], and these layers are summed over various ranges to estimate the mass of ozone in the polar vortex. The mass of air in the vortex is estimated in the same manner, Figures 6a-d show the sums from the lower to upper stratosphere (covering 400- 1570 K). In the NH both ozone and air mass are decreasing in early winter. This reflects mainly the motion of these isentropes to lower pressure, as the stratosphere cools. Of the three NH winters studied, because the lower stratosphere is warmest (coldest) in 1993/1 994 (1992/1 993) in the NH, the air mass is greatest (least) between two given isentropes. In the SH, the areal extent of the vortex is significantly larger, but colder temperatures raise the isentropes to lower pressure, so the total masses are similar in the two hemispheres. in early winter, the slight increases in ozone mass in the SH vortex generally follow those of the air itself. In late winter, the ozone and air mass in the NH show different trends in each year; as will be shown below, this is due to the combined effect of opposing trends above and below 690 K. In the S14, the air mass is slightly decreasing in late winter. However, the SH decrease in ozone mass is large compared to that in the air mass, consistent with widespread chemical depletion of ozone.

Fig. 6e through 6h show the ozone mass between 690 and 1570 K, in the middle and upper stratosphere, and Fig. 6i through 61, the ozone mass between 400 and 690 K, in the lower stratosphere. in early winter, the distribution of ozone is similar in the two hemispheres, with ≈30% of the ozone mass in the vortex in the middle and upper stratosphere. In contrast, in late winter, the ozone mass increases rapidly in the middle and upper stratosphere in the NH, and only slightly in the SH, so that near the end of these time series there may be up to twice as much ozone mass in the NH middle and upper stratospheric vortex as in the SH.

The two dynamical effects discussed above also influence these estimates for the upper and lower stratosphere separately. The fact that the ozone mass is frequently larger in the lower stratosphere in the S11 late winter than in the N] I despite the large SH chemical ozone 1oss (Figure 6j and 61) is due to the greater size of the SH lower-stratospheric vortex. Lower temperatures in the SH result in less mass in a given area and isentropic layer; this, as well as weaker poleward transport, contributes to smaller SH ozone mass in the middle and upper stratospheric vortex. An additional difficulty in using a single I'V contour at each level to define the vortex area is that the chosen contour may include more of the vortex edge region during some periods than others, The high ozone mass in the NH middle and upper stratosphere in late winter 1992 (Fig. 6f) is due in part to the fact that the chosen PV contour lies farther on the outer edge of the region of strong PV gradients (Fig. 3), where ozone mixing ratios are larger. The NH ozone mass for late winter 1992 may thus be somewhat overestimated, but is still expected to be larger than for 1993 and 1994 in late winter. These dynamical effects make it difficult to interpret the trends shown in Fig. 6 in terms of changes in column ozone. However, Froidevaux et al. [1994, submitted to *J. Atmos. Sci.*], clearly show that the column above the 22 hPa pressure level contributes considerably mm-e to the total column at high latitudes in the NH than in the SH. Since the ozone decrease in the N} I lower stratosphere in 1993 is less than that typically seen in the SH, and since there is a larger contribution from the middle and upper stratosphere, where ozone is increasing rapidly, the chemical depletion of ozone in the NH lower stratosphere in late winter 1993 was not evident in the column.

Synoptic Evolution in Late Winter

We examine here some details of the synoptic evolution of ozone in the middle ant] lower stratosphere during late winter, when there is considerable dynamical variability. Some aspects of the synoptic evolution of ozone in early winter are discussed by Manney et al. [1994, submitted to *Q. J. Roy. Meteor.* Sot.].

Figure 7 shows synoptic maps of ozone and several PV contours at 840 and 465 K in February and March 1992. This is after the warming event in late January, and the polar vortex remains relatively weak in the mid-stratosphere. Although no major warming occurs during this time period, the vortex at 840 K is highly distorted, and high ozone can clearly be seen being drawn into the polar regions from low latitudes.

At 465 K, ozone is seen to increase slightly in the polar vortex between 16 February and 15 March 1992; this is expected from descent of higher ozone [Manney et al. 1994a]. Since the late January warming resulted in temperatures rising well above those necessary for the formation of PSCs, and since ClO had decreased considerably by 16 February [Waters et al. 1993a], any chemical loss is too small to modify the expected dynamical effect, The vigorous wave activity that is typical of the NH winter is obvious in the distorted shape of the polar vortex at 465 K, and on 16 February and 9 March, narrow tongues of high ozone can clearly be seen being stripped off the edge of the vortex in the lower stratosphere.

Figure 8 shows similar figures for several days in February and March 1993. The polar vortex was still strong on 10 February, although shifted well off the pole. 24 February and 6 March are in the midst of two strong stratospheric warmings. The later warming leads into the final warming [Manney et al. 1994b]. At 840 K in the mid-stratosphere, large tongues of ozone are nearly continuously being drawn into the polar regions at this time. There is little obvious evidence of material being drawn off the vortex, until the time of the major warming (6 March and 14 March plots). The blob of low ozone that appears in the low PV region (the "Aleutian high") on some of these days is a common feature in the NH winter, and chemical effects are thought to be important in its origin [Manney et al. 1994, paper in preparation].

At 465 K, the vortex remains strong and highly distorted during this time period, and its shape changes very rapidly from day to day. On some days, including 6 March 1993, the vortex reaches quite low latitudes. The main difference between 1993 and other years for which ozone has been observed in the NH is that, between 10 Feb and 14 Mar, the ozone mixing ratio decreases significantly in the polar vortex, with the sharpest decrease during late February [Manney et al. 1994a]. As during, the previous year, some filaments of air with relatively high ozone mixing ratio are seen being drawn off the edge of the vortex,

Figure 9 shows the vertical distribution of ozone and the vertical structure of the polar vortex for the same days in Feb and Mar 1993. Fig, 9a through 9d are cross-sections showing ozone and scaled PV as a function of longitude and θ, at 64^{O}N; Fig. 9e through 9h are cross-sections showing ozone and scaled PV as a function of latitude and (?, along O to 180^{O} longitude, As noted by Manney et al. [1994f], the polar vortex tilts westward and equatorward with increasing altitude during the intensification of stratospheric warmings; this behavior can be seen in the cross-sections on 24 Feb and 6 Mar, although both these days are near the peak of the warmings [Manney et al. 1994b], when the westward tilt with height has decreased [Manney et al. 1994f]. Near the edge of the vortex, ozone profiles frequently show complex and rapidly varying vertical structures, with values characteristic of the exterior of the vortex at some levels, and of the interior at others. Figure 10 shows four individual ozone profiles from MLS between 55° and 60^{O}N, ranging from ≈320 to 360^{O}E longitude on 6 Mar 1993. The western-most profile is entirely outside the vortex, although it is near the edge at the lower levels; the eastern-most one is entirely inside, The ozone values in the third profile indicate that it was sampling air inside the vortex at 4.6 hPa, and outside at 10 hPa.

Figure 11 shows synoptic maps at 840 K and 465 K during Feb and Mar 1994. At this time, the vortex is relatively strong in the middle stratosphere, but is weak in the lower stratosphere until late in the period shown. In the middle stratosphere, although there are no strong warmings at this time, we once again see tongues of high ozone being drawn around the vortex from low latitudes, and some evidence (e.g. 7 and 11 Feb) of tails of low ozone being drawn off the vortex. in the lower stratosphere, ozone in the vortex increases between 7 and 23 Feb, as would be expected from diabatic descent. A decrease is seen between 23 Feb and 12 Mar 1994. At this time, the lower stratosphere cooled below the threshold for PSC formation for approximately two weeks, and MLS observed enhanced ClO in the vortex, indicating the possibility of chemical loss of ozone.

We note that in 1994, there are considerably larger areas of relatively high ozone outside the vortex at 465 K than in 1993, and larger areas in 1992 than in 1993. Figure 3 showed that, throughout the winter (before mid-February), the lower stratospheric polar vortex was weakest in 1994 and strongest in 1993 in the NH. The patterns of high ozone seen at mid-latitudes confirm that ozone is significantly more confined within the vortex in 1993 than in 1994, consistent with the relative strength of the lower stratospheric vortex in those years. Because the vortex is stronger in the lower stratosphere when temperatures are colder, those years in which there is most potential for the activation of chlorine and the associated chemical destruction of ozone will also generally be those in which the air in the lower stratospheric vortex is most confined during winter. Downward transport supplies higher ozone from above throughout the vortex, and near the vortex edge, since significant diabatic descent is confined to those regions [e.g., Schoeberl et al. 1992, Manney et al. 1994d, submitted to *J. Atmos. Sci.*]. Thus, most of the higher ozone values are expected to originate from the vortex or the region near the vortex edge; examination of synoptic maps throughout the observed part of the winter shows that filaments of high ozone being drawn out into mid-latitudes from the vicinity of the vortex edge are a regular occurrence, but are larger and drawn off more frequently in 1994 than in 1992 or 1993, Calculations comparing transport in the lower stratosphere for early 1993 and early 1994 confirm that the lower stratospheric vortex is a considerably weaker barrier to tranport into mid-latitudes from the vortex edge region in 1994 than in 1993 [Manney et al. 1994d, submitted to *J. Atmos. hi.*].

Synoptic maps for the SH 1992 winter in the mid- and lower stratosphere were shown by Manney et al. [1993] and Waters et al. [1993b]. These showed the effects of chemical destruction of ozone in the lower stratosphere. In the mid-stratosphere, evidence of poleward transport of ozone was apparent during the minor warmings in late August and September, as tongues of ozone were drawn into the polar regions [Manney et al. 1993].

Figure 12 shows SH ozone at 840 K and 465 K in August and September 1993, 23 Aug is near the peak of a relatively strong minor warming; 14 Sep is at the beginning of another, Although the strongest warmings in the SH are considerably weaker than those that commonly occur in the NH, many similar features are noted in the behavior of the polar vortex and the ozone in the mid-stratosphere during these events. These include large tongues of high ozone being drawn into the polar regions, and some evidence for tongues of low ozone being drawn off the vortex.

As in 1992, [Manney et al. 1993, Waters et al. 1993a,b] the S11 465 K ozone fields for 1993 show marked effects of chemical destruction of ozone. As can be seen in the time series shown in the previous sections, lower stratospheric ozone is lower during Aug and Sep 1993 than in 1992. Although some narrow filaments of higher ozone are seen being drawn off the edge of the vortex at 465 K, the extent of regions of higher ozone outside the vortex is less than in any of the NH winters, consistent with the stronger and less disturbed lower stratospheric vortex in the SH.

Figure 13 shows vertical cross-sections of ozone and scaled PV similar to those shown in Fig. 9 for the NH, on 23 Aug and 14 Sep 1993. A westward and equatorward tilt of the polar vortex and the ozone field with height is apparent on 23 Aug, as is typical during stratospheric warmings. Because of the larger role that chemical destruction plays in the lower stratosphere in the SH, there is an obvious drop in ozone mixing ratios in crossing from outside to inside the vortex at the lowest levels shown in these plots. A similar, although much less obvious drop, is seen in the NH during 1993 (Figure 9). Figure 14 shows individual ozone profiles across the edge of the vortex on 23 Aug. The vortex tilts strongly westward with height on this day, and although the westernmost profile sampled air from within the vortex at all levels, the other profiles shown sample air from within the vortex up to 22 hPa, and air from outside the vortex above this level,

Summary and Conclusions

The time evolution of UARS MLS ozone throughout the stratosphere during winter is shown in relation to the evolution of the stratospheric polar vortex for three NH and two S11 winters. The genera] results show poleward and downward transport of ozone throughout the stratosphere during December through March in the NH and June through September in the SH, consistent with previous theoretical [e.g., Rood and Schoeberl

1983; Wu et al. 1987; Fisher et al. 1993; Manney et al. 1994d, submitted to JAS] and observational [Wu et al. 1985, Manney et al. 1993] studies. Overall increases in high-latitude ozone in the middle and upper stratosphere between early and late winter were seen in the NH in 1991/1992 and 1992/1993, even at levels above the ozone mixing ratio peak, indicative of strong poleward transport at these levels. In the 1993/1994 NH and the 1992 and 1993 SH late winter-s, ozone is still less than the early winter values above the mixing ratio peak but greater below, reflecting the effects of downwelling.

Planetary wave activity increases during late winter in both hemispheres, weakening. and shrinking the polar vortex. Rapid increases are seen in vortex ozone in the middle and upper stratosphere during stratospheric warmings. Planetary wave activity is more persistent in the NH than in the SH, thus the NH polar vortex is weaker and more distorted, The corresponding NH high-latitude ozone increases in the middle and upper stratosphere are much larger than in the SH. The rapid increase in vortex ozone during warming events can be followed by a decrease if the vortex recovers. Both poleward and downward transport are enhanced during stratospheric warmings, results of transport by planetary scale waves and increased diabatic descent due to larger departures from radiative equilibrium. High latitude ozone increases during strong stratospheric warmings even at levels above the mixing ratio peak, indicating that horizontal transport is particularly important in the middle and upper stratosphere during such events. In the three NH winters shown, the increase in mid-stratospheric polar ozone is related to the timing, intensity and persistence of stratospheric warmings. Much less increase is seen in mid and late winter 1994, when the NH mid-stratospheric vortex remains relatively strong and undisturbed compared to the other years. in this regard, the 1993/1994 NH winter resembled those in the SH. However, the SH vortex is even stronger and only a small increase in ozone mixing ratio in the high latitude mid-stratosphere is seen over the winters; this small increase is again associated with increasing wave activity in late winter, Ozone decreases during late winter in the SH lower stratosphere, consistent with destruction by chlorine chemistry [Waters et al. 1993b]. Conditions there are favorable for heterogeneous chemistry to occur (i.e., low temperatures, high ClO [Waters et al. 1993a, b], presence of polar stratospheric clouds [Mergenthaler et al. 1993] 93]) for a sufficiently long time that the changes are large and can be attributed with confidence to chemical destruction of ozone. The behavior in the NH is more ambiguous. Evidence was previously presented suggesting chemical destruction of ozone in the lower stratosphere during January and February 1992 [Waters et al. 1993a]; Manney et al. [1994a] demonstrated that the decrease in ozone in February and March 1993 could only be explained by chemical depletion. In late February and early March 1994, a decrease is seen in lower stratospheric ozone, concurrent with a decrease in temperatures and enhancement of C1O. This suggests chemical ozone depletion at this time; further analysis is underway to determine whether any dynamical processes cou 1 d have caused ozone to decrease.

The synoptic evolution of ozone and the polar vortex is shown during late winter 1992, 1993 and 1994 in the NH, and 1993 in the SH, The NH mid-stratospheric polar vortex is always distorted, and tongues of high ozone are drawn into the NH polar regions throughout late winter. In 1993, this behavior intensifies during the stratospheric warmings, and long narrow tongues of low ozone are drawn off the vortex around the anticyclone in the mid-stratosphere. in the SH, the mid-stratospheric vortex is more symmetric about the pole except during warmings, and tongues of high ozone are drawn into the polar regions only at the time of stratospheric warmings. only during the peak of the warmings is it obvious that low ozone is being drawn off the vortex, The tongues of high ozone pulled into high latitudes reflect the enhanced poleward transport associated with stratospheric warmings.

Synoptic maps of ozone in the NH lower stratosphere demonstrate a relationship between the extent of higher ozone values seen at middle latitudes, outside the vortex, and the strength of the lower stratospheric vortex, as indicated by the 465 K PV gradients. in 1994, the lower stratospheric vortex was considerably weaker during most of the NH winter than in 1992 or 1993, and much larger areas of higher ozone are seen outside the vortex in 1994. Manney et al. [1994a] showed that in Feb 1979, during a NH winter when the lower stratospheric vortex was even weaker than in 1994 [Zurek et al. 1994, paper in preparation], even larger areas of relatively high ozone (from LIMS measurements) are seen outside the vortex. The degree of isolation in the NH winter is thus quite variable, and lower stratospheric ozone is expected to be much more confined in the vortex during winter in the coldest years, As discussed by Froidevaux et al. [1994, submitted to *J. Atmos. Sci.*], MLS observed low column ozone in the 30° to 60°N latitude band in the NH late winter of 1993, consistent with the anomalously low TOMS observations [Gleason et al. 1993, Herman and Larko 1994]; these low column values came primarily from lower ozone between 100 and 46 hPa. Although part of this is thought to be due to effects from Pinatubo, some aspects are difficult to explain by those processes alone [see discussion by Froidevaux et al. 1994, submitted to *J. Atmos. Sci.*]. As shown here, the problem is further complicated by dynamical effects which tend to result in lower midlatitude ozone in the NH winter of 1992/1 993.

The differences in wave activity and strength of the polar vortex between NH and SH result in very different vertical distributions of ozone in the polar regions of the two hemispheres in late winter, In the NH late winter, the middle and upper-stratosphere contribute much more to the total ozone column than in the SH. This makes it difficult if not impossible to diagnose changes in lower stratospheric ozone solely from column measurements.

Acknowledgments. Thanks to our MLS colleagues for their contributions to its success; to the UKMO, especially A. O'Neill and R. Swinbank, for making available the UKMO meteorological analyses; to T. Luu for data management; to B. P. Ridenoure for graphics and data analysis assistance; to P. A. Newman for supplying routines that were adapted to calculate PV. The UARS investigations at the Jet Propulsion Laboratory, California Institute of Technology were carried out under contract with the National Aeronautics and Space Administration.

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Figure Captions

Figure 1. Thirty-day averages of zonal mean ozone mixing ratio (ppmv) as a function of latitude and pressure, for (a) to (e) early winter and (f) to (j) late winter; and (k) to (o) the difference (ppmv) between late winter and early winter plots for each winter, with dashed contours indicating less ozone in late winter. The labeled pressure levels correspond to those at which MLS ozone is current] y retrieved.

Figure 2. Thirty-day averages of ozone mixing ratio (ppmv) averaged around a PV contour, as a function of PV and potential temperature, θ, for the same time periods shown in Fig. 1. Vertical line at $1.4 \times 10^{-4}\ s^{-1}$ shows the PV contour enclosing the area over which averages are taken in Fig. 5.

Figure 3. Area integrals of PV for 120 days starting 1 Dec in the NH and 1 Jun in the SH, (a) to (e) 840 K in the mid-stratosphere, and (f) to (j) 465 K in the lower stratosphere. The contours are scaled PV, from 0.8×10^{-4} to $3.0 \times 10^{-4}\ s^{-1}$, with a contour interval of $0.2 \times 10^{-4}\ s^{-1}$; the bold contour is $1.4 \times 10^{-4}\ s^{-1}$. Heavy horizontal bars near the bottom of the 840 K plots show the averaging periods used in Figs. 1 and 2. Arrowheads indicate approximate times of the peaks of significant stratospheric warmings, as discussed in the text. The discontinuity on ≈5 Dec 1991 in the 840 K contours is due to changes in the UKMO analyses at this time [Swinbank and O'Neill 1994].

Figure 4. Time series as a function of θ of minimum daily temperatures (K) at scaled PV values greater than $1.4 \times 10^{-4}\ s^{-1}$. The contour interval is 5 K, with dark shading below 195 K (a typical threshold for PSC formation in the lower stratosphere), and light shading between 205 and 210 K.

Figure 5. Time series for early and late winter MLS high latitude observing periods of ozone mixing ratio (ppmv) averaged over the area where the scaled PV is greater than $1.4 \times 10^{-4}\ s^{-1}$, as a function of θ. The contour interval is 0.2 ppmv, with dark

shading between 2.4 and 2.6 ppmv, and light shading between 6.0 and 6.2 ppmv. Blank spaces in the interior of individual series are either days when sufficient data were missing that the gridding procedure could not be applied, or days when there are known data problems in high latitudes.

Figure 6. (a) through (d) estimates of ozone and air mass in the stratospheric polar vortex between 400 and 1570 K for early and late winter. Green line shows 199 1/1 992, blue line 1992/1 993, red line 1993/1 994 in the NH; green line shows 1992 in the SH and blue line shows 1993. See text for details of calculation. (e) through (h) estimates of ozone mass in the polar vortex between 690 and 1570 K, (i) through (1) estimates of ozone mass in the polar vortex between 400 and 690 K.

Figure 7. Synoptic maps of ozone mixing ratios (ppmv) with overlaid PV contours at 840 K and 465 K, on 16 Feb 1992, 26 Feb 1992, 9 Mar 1992 and 15 Mar 1992 in the NH. Overlaid PV contours at 840 K are from 3.0 to 6.0 x 10^{-4} K m^2 kg^{-1} s^{-1} , with a contour interval of 1.0 x 10-4 K m^2 kg^{-1} s^{-1}; PV contours at 465 K are from 0.2 to **0.35** x 10-4 K m^2 kg^{-1} s^{-1}, with a contour interval of 0.05 **x 10-4** K m^2 kg^{-1} s^{-1}. Projection is orthographic, with 0° longitude at the bottom of the plot, and 30 and 60^{o} latitude circles shown as thin dashed lines.

Figure 8. As in Fig. 7, but for 10 Feb 1993, 24 Feb1993, 6 Mar 1993 and 14 Mar 1993.

Figure 9. Vertical sections of ozone mixing ratios and scaled PV contours for the days shown in Fig. 8. (a) through (d) show longitude/θ sections at 64^{o}N; (e) through (h) show latitude/θ section across the pole along 0° to 180^{o} longitude. Units of scaled PV are 1 0-4\- 1 .

Figure 10. individual ozone profiles on 6 Mar 1993, crossing the vortex edge. Approximate profile locations are indicated in Fig. 8.

Figure 11. As in Fig. 7, but for 7 Feb 1994, 11 Feb 1994,23 Feb 1994 and 12 Mar 1994.

Figure *12.* As in Fig. 7, but for the SH on 9 Aug 1993, 23 Aug 1993,4 Sep 1993 and 14 Sep 1993.0° longitude is at the top of the plots.

Figure 13. As in Fig. 9, but for the SH on 23 Aug 1993 and 14 Sep 1993, and with (a) and (b) at 60°S latitude.

Figure 14. As in Fig. 10, but for 23 Aug 1993 in the SH.

TABLE 1: UARS MLS HIGH-LATITUDE WINTER COVERAGE

SEASON HEMISPHERE	NOMINAL HIGH-LATITUDE COVERAGE DATES	DAYS OF MISSING OR INCOMPLETE DATA
EARLY WINTER		
NH	05 Dec 91 - 13 Jan 92	-------
NH	30 Nov 92-08 Jan 93	-------
NH	26 Nov 93 - 04 Jan 94	3-4 Dec 93 ; 24-25 Dec 93
s H	01 June 92-12 July 92	1-14, 18-19, 23-26 June 92 8-9 July 92
S H	29 May 93-07 July 93	-------
LATE WINTER		
NH	15 Feb 92-22 Mar 92	-------
NH	10 Feb 93 - 19 Mar 93	15 Mar 93
NH	05 Feb 94 - 14 Mar 94	28 Feb -1 Mar 94 4-7 Mar 94
s H	14 Aug 92-21 Sept 92	-------
SH	09 Aug 93-16 Sept 93	-------

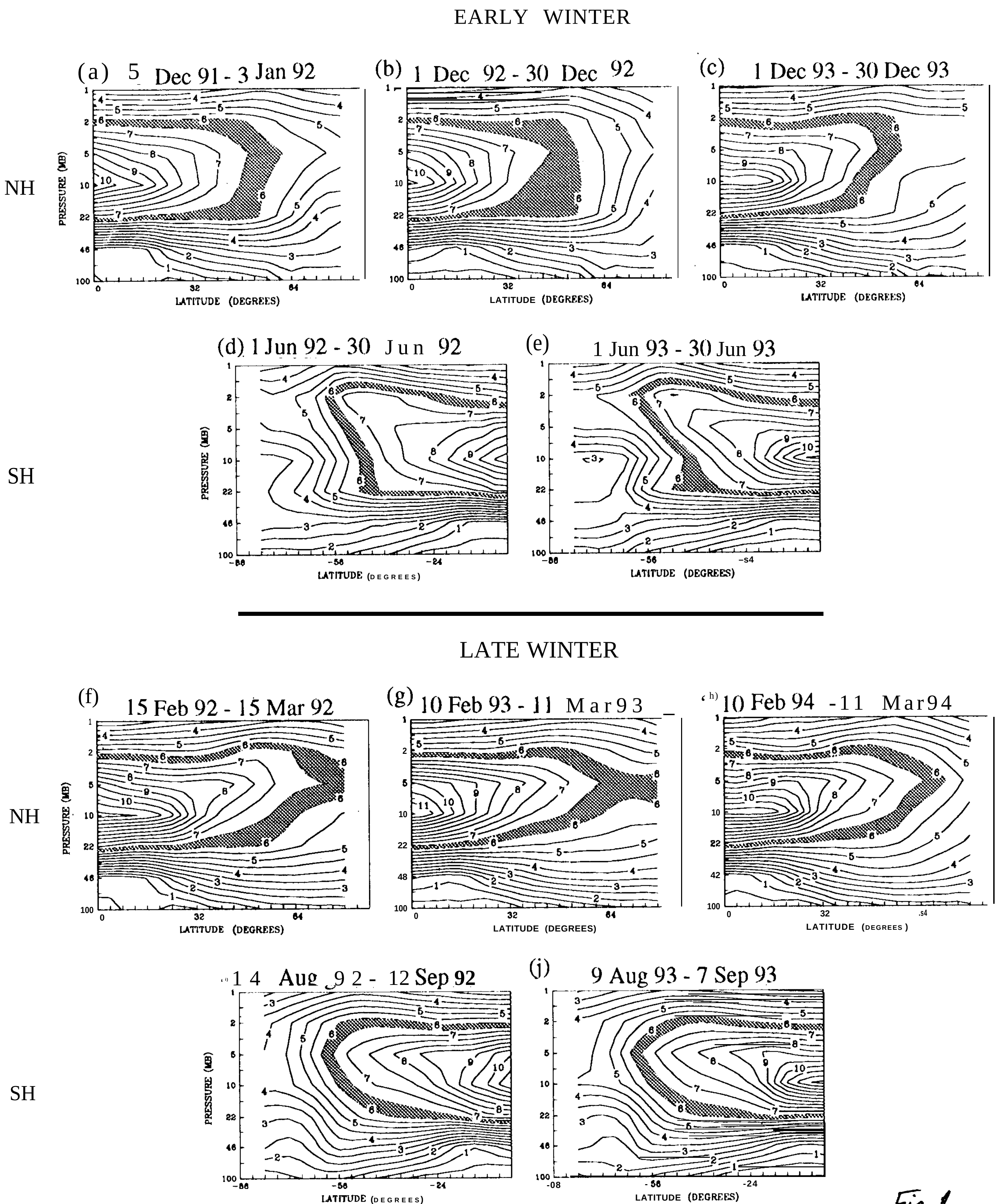

EARLY WINTER
NH
(a) 5 Dec 91 - 3 Jan 92
(b) 1 Dec 92 - 30 Dec 92
(c) 1 Dec 93 - 30 Dec 93
SH
(d) 1 Jun 92 - 30 Jun 92
(e) 1 Jun 93 - 30 Jun 93
LATE WINTER
NH
(f) 15 Feb 92 - 15 Mar 92
(g) 10 Feb 93 - 11 Mar93
(h) 10 Feb 94 -11 Mar94
SH
(i) 14 Aug 92 - 12 Sep 92
(j) 9 Aug 93 - 7 Sep 93
PRESSURE (MB)
LATITUDE (DEGREES)

Fig. 1

LATE WINTER MINUS EARLY WINTER

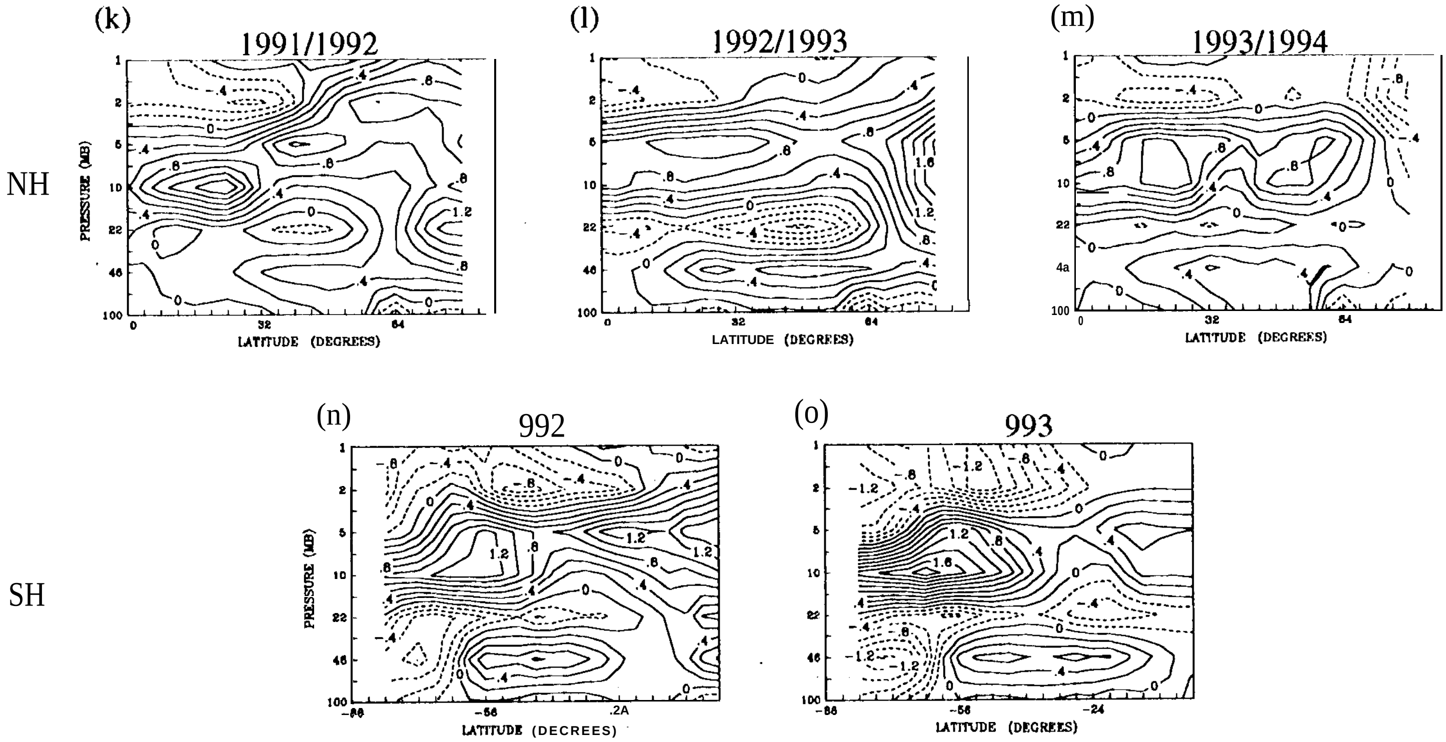


Fig. 1 con't

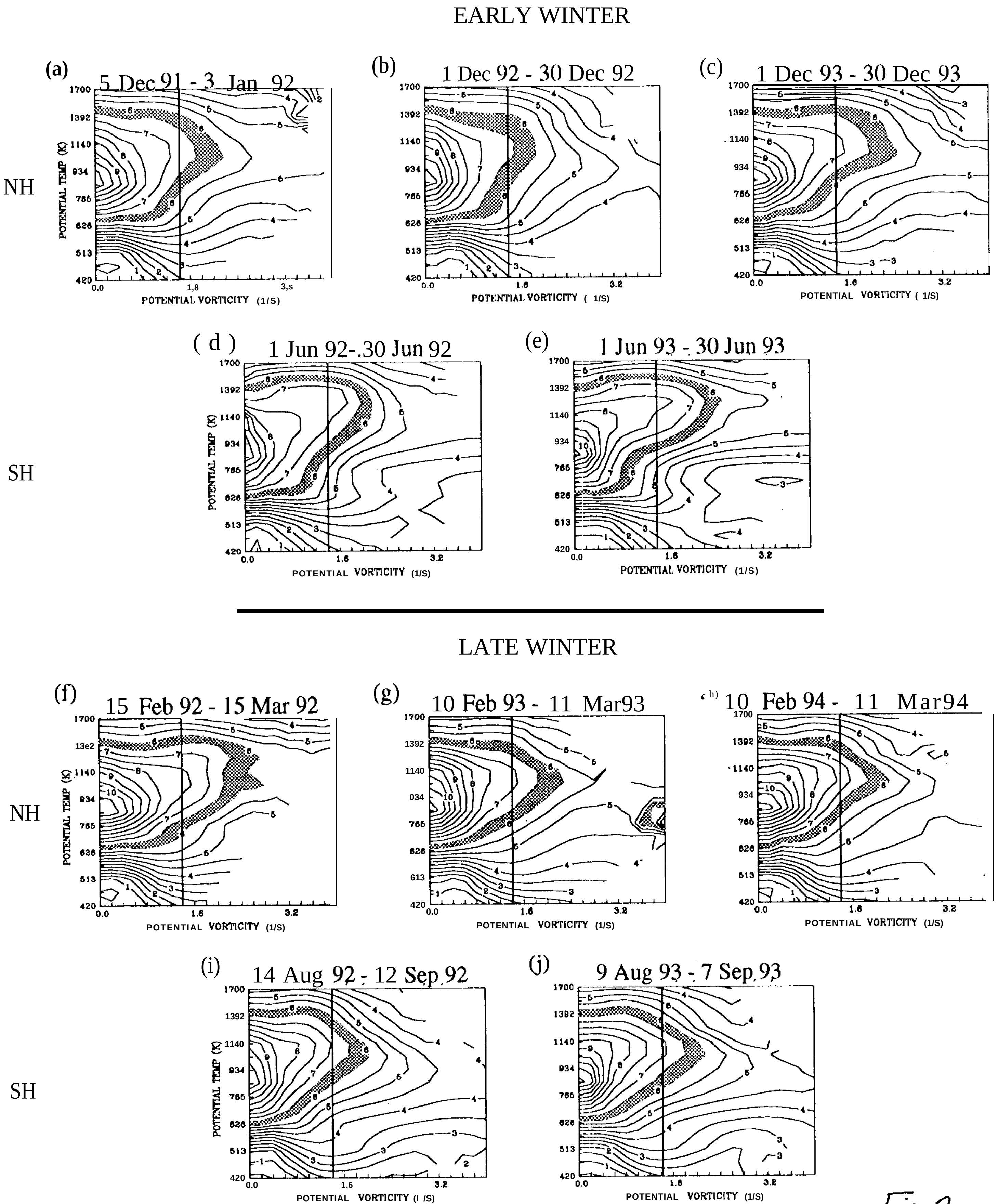

EARLY WINTER
NH
(a) 5 Dec 91 - 3 Jan 92
(b) 1 Dec 92 - 30 Dec 92
(c) 1 Dec 93 - 30 Dec 93
SH
(d) 1 Jun 92 - 30 Jun 92
(e) 1 Jun 93 - 30 Jun 93
LATE WINTER
NH
(f) 15 Feb 92 - 15 Mar 92
(g) 10 Feb 93 - 11 Mar93
(h) 10 Feb 94 - 11 Mar94
SH
(i) 14 Aug 92 - 12 Sep 92
(j) 9 Aug 93 - 7 Sep 93
POTENTIAL TEMP (K)
POTENTIAL VORTICITY (1/S)

Fig. 2

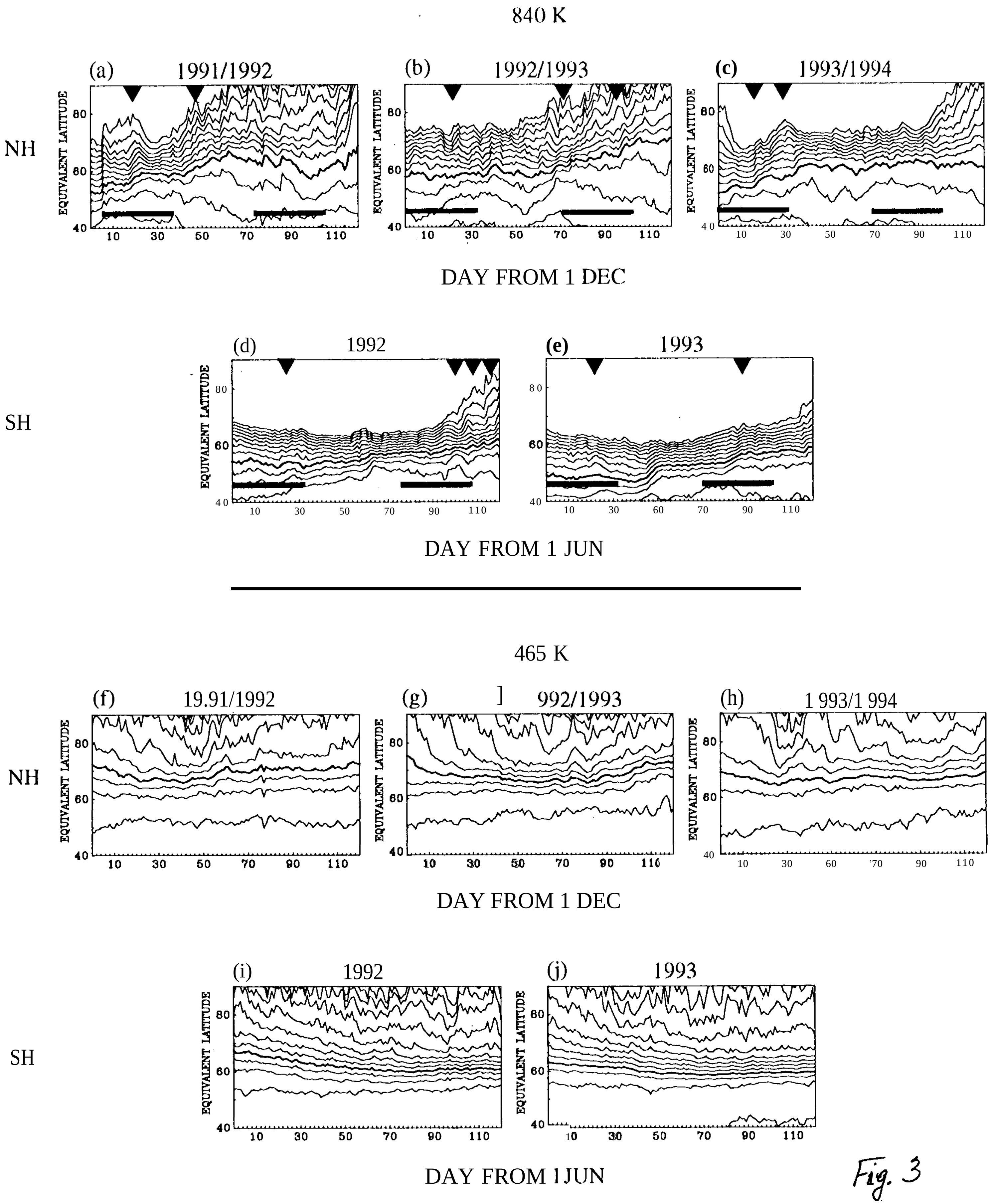

840 K
(a) 1991/1992
(b) 1992/1993
(c) 1993/1994
NH
EQUIVALENT LATITUDE
DAY FROM 1 DEC
(d) 1992
(e) 1993
SH
DAY FROM 1 JUN
465 K
(f) 19.91/1992
(g)] 992/1993
(h) 1 993/1 994
NH
DAY FROM 1 DEC
(i) 1992
(j) 1993
SH
DAY FROM 1JUN

Fig. 3

MINIMUM VORTEX TEMPERATURE

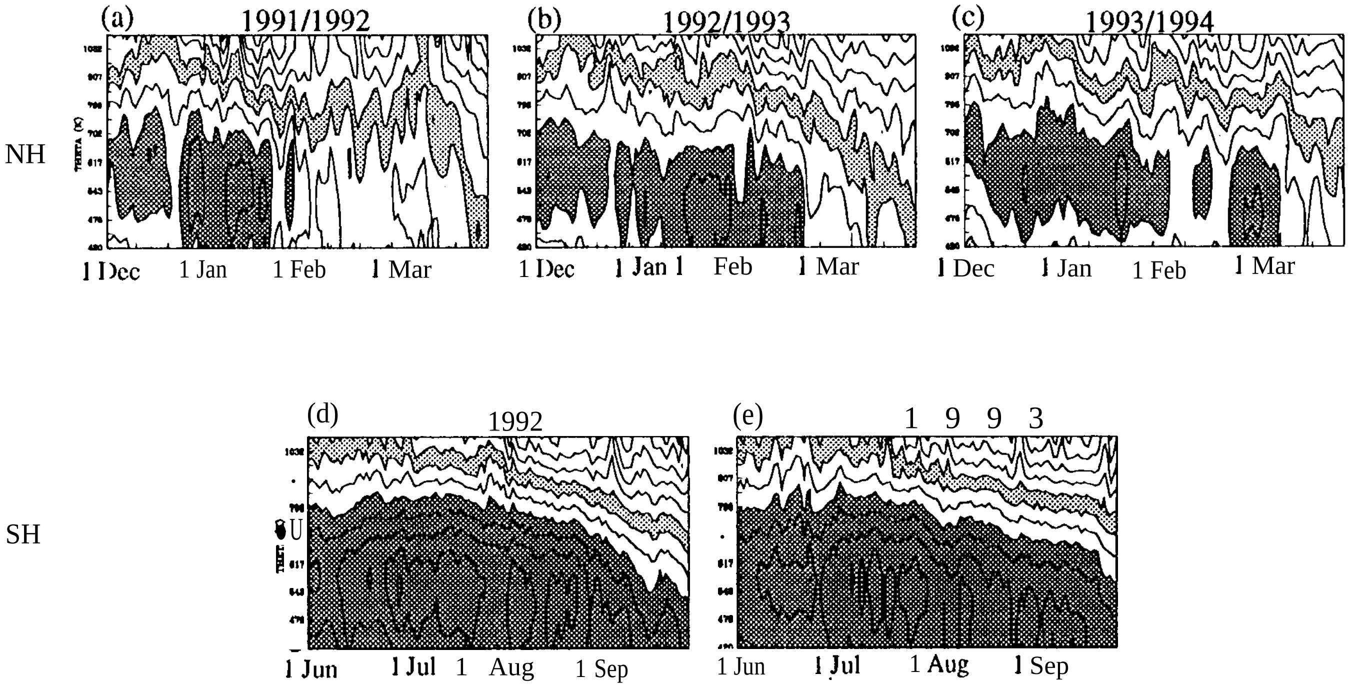


Fig. 4

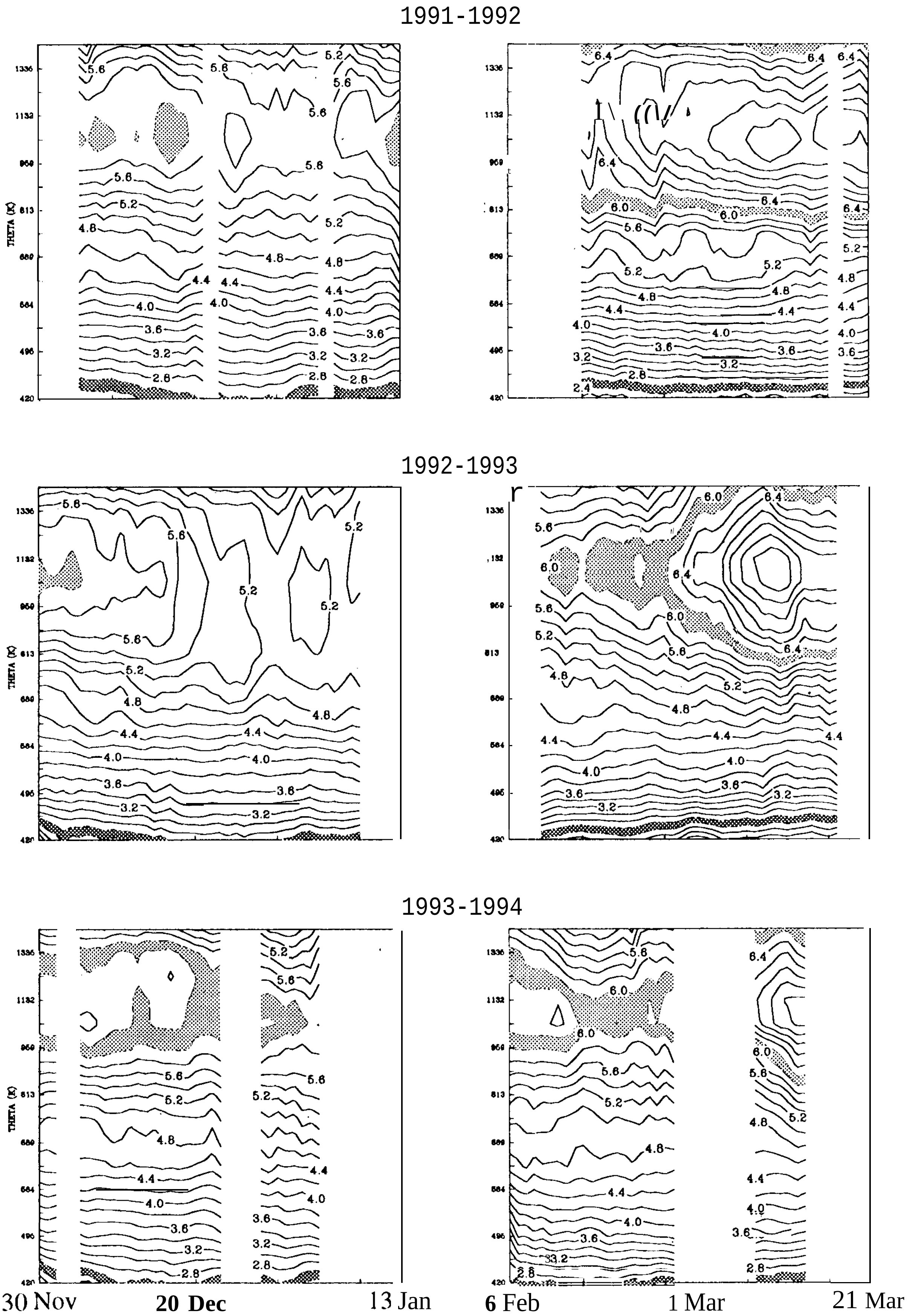

1991-1992
1992-1993
1993-1994
THETA (K)
1336
1132
959
813
689
584
495
420
30 Nov
20 Dec
13 Jan
6 Feb
1 Mar
21 Mar

Fig. 5

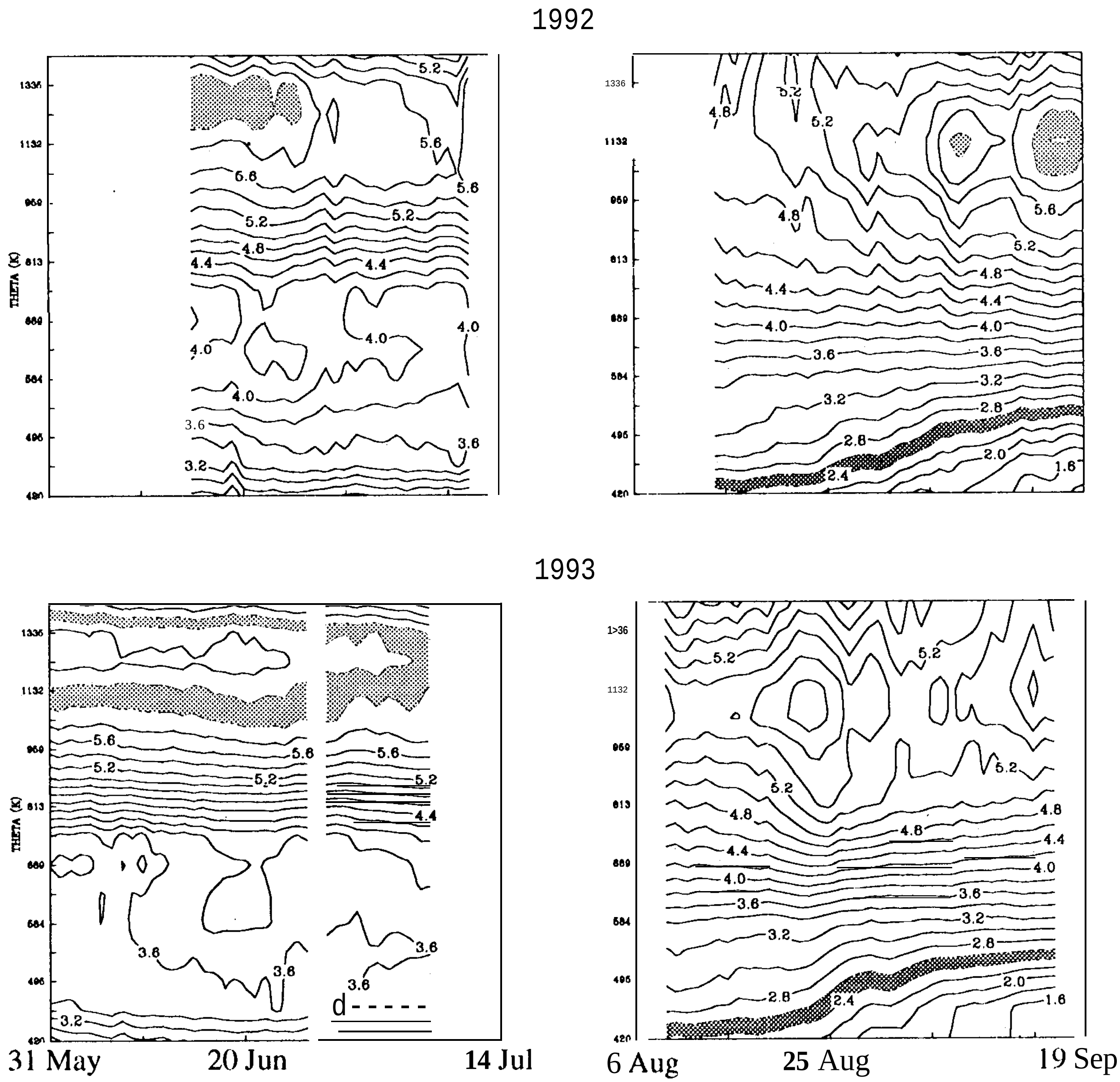
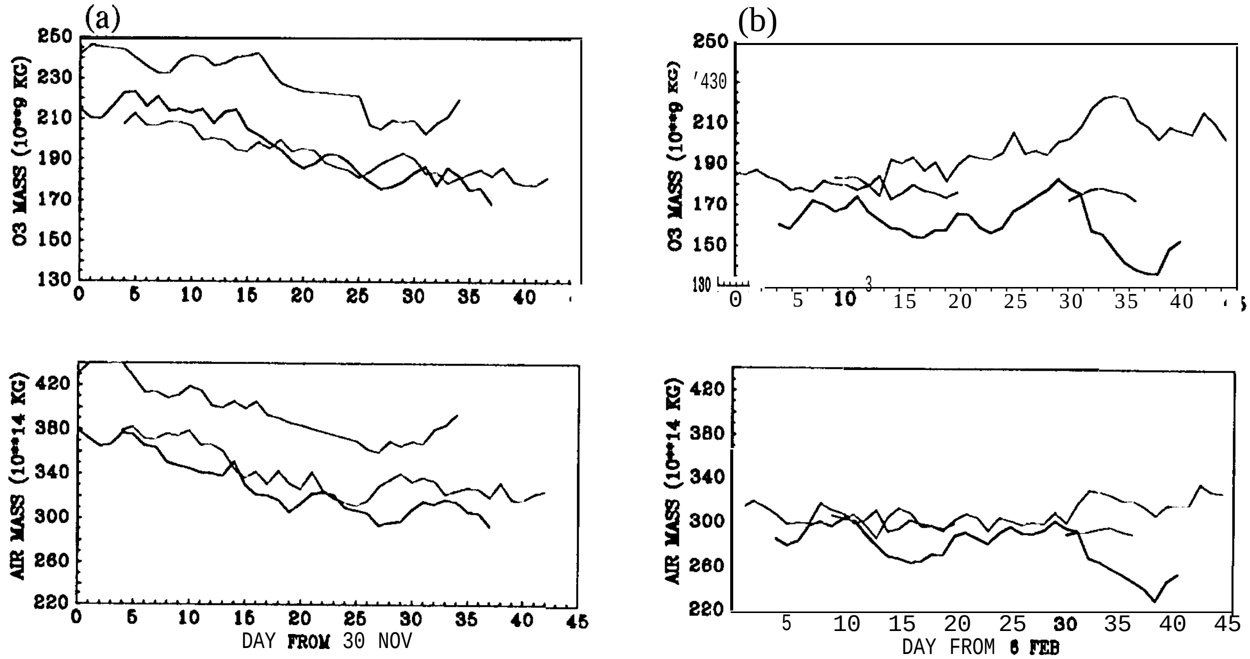
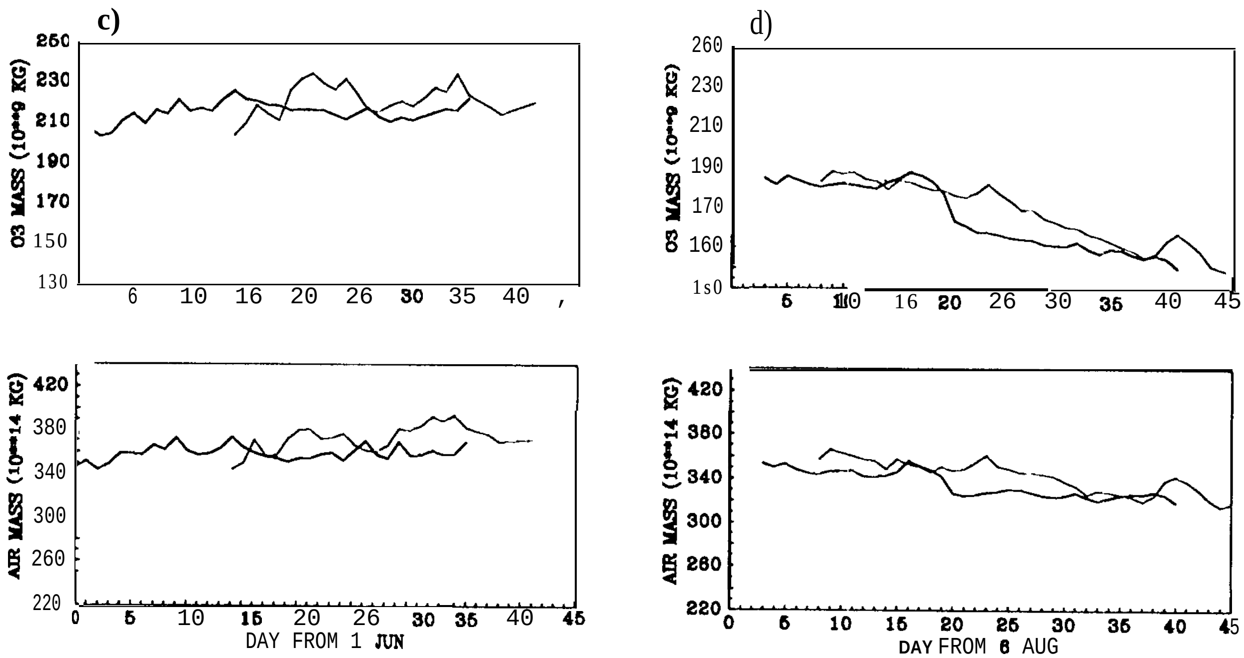

1992
1993
THETA (K)
1336
1132
959
813
669
584
496
420
31 May
20 Jun
14 Jul
6 Aug
25 Aug
19 Sep
d

Fig. 5 con't

Northern Hemisphere, 400-1570 K



Southern Hemisphere, 400-1570 K



—— NH 1991/1992, SH 1992

‾NH 1992/1993, SH 1993

— NH 1993/1 994

Fig. 6

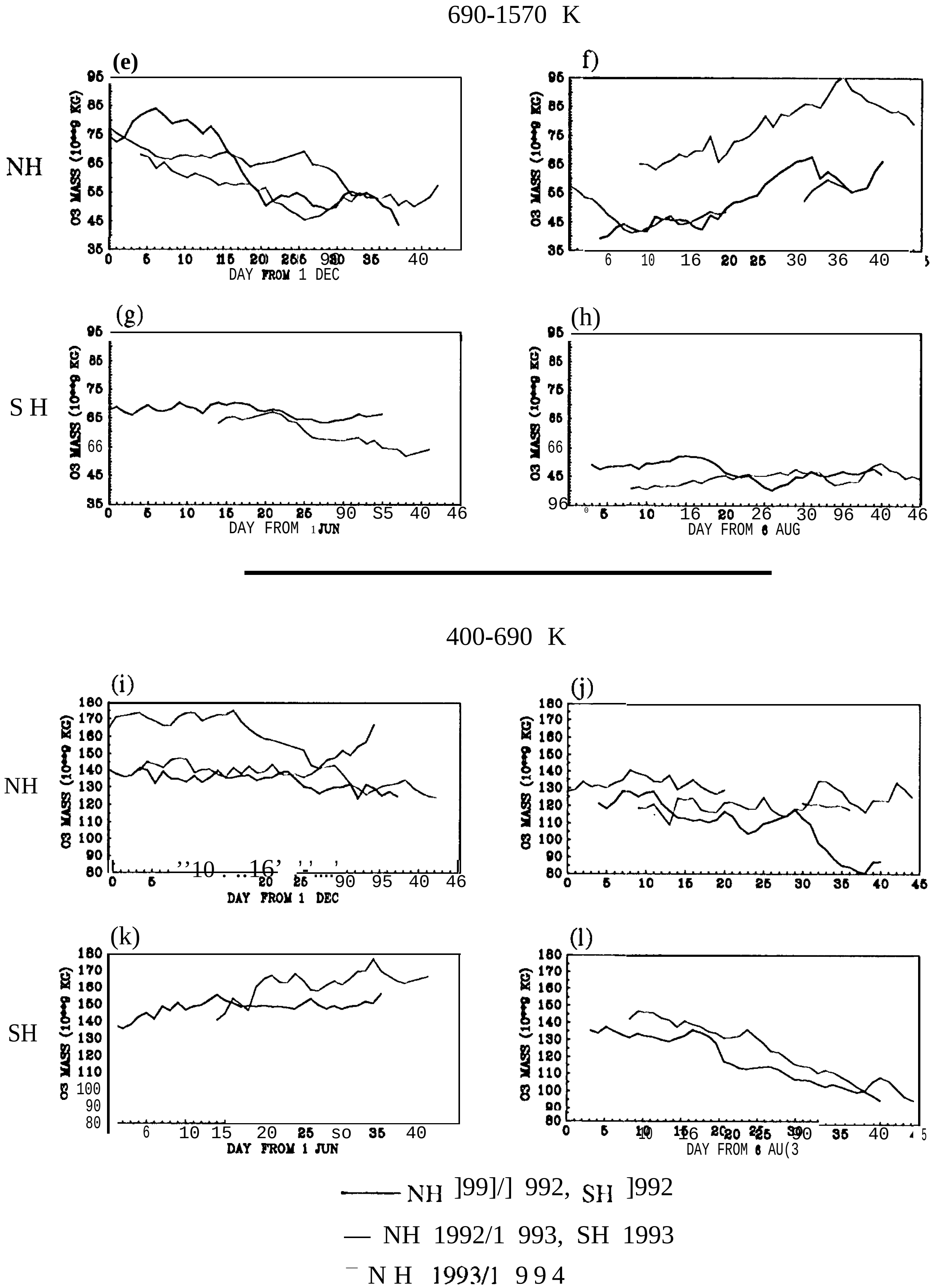

690-1570 K
(e)
f)
NH
O3 MASS (10**9 KG)
DAY FROM 1 DEC
(g)
(h)
S H
DAY FROM 1 JUN
DAY FROM 6 AUG
400-690 K
(i)
(j)
NH
(k)
(l)
SH
— NH 1991/1992, SH 1992
— NH 1992/1993, SH 1993
— NH 1993/1994

Fig. 6 cont

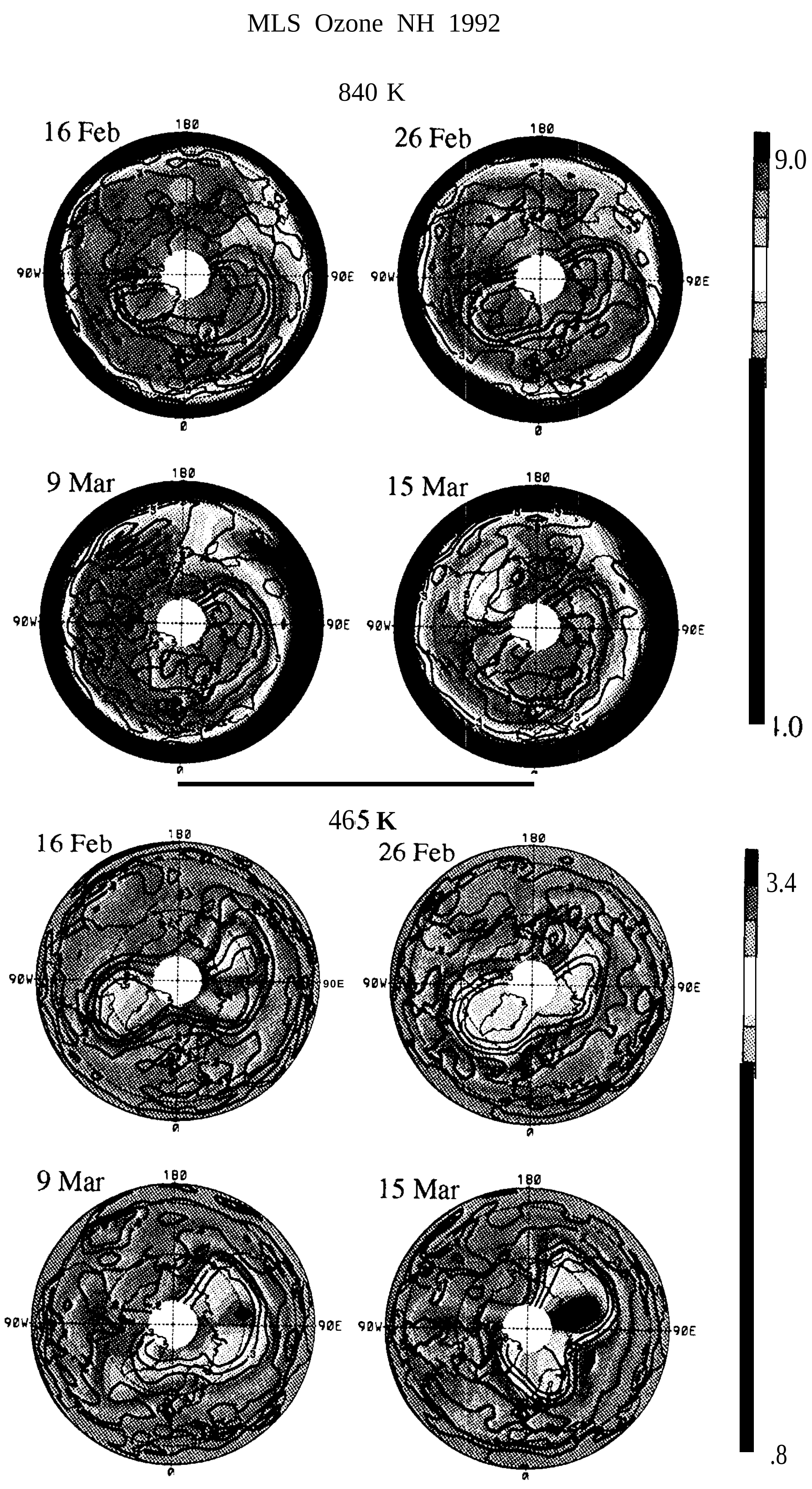

MLS Ozone NH 1992
840 K
16 Feb
26 Feb
9 Mar
15 Mar
9.0
1.0
465 K
16 Feb
26 Feb
9 Mar
15 Mar
3.4
.8
180
90W
90E
0

Fig. 7

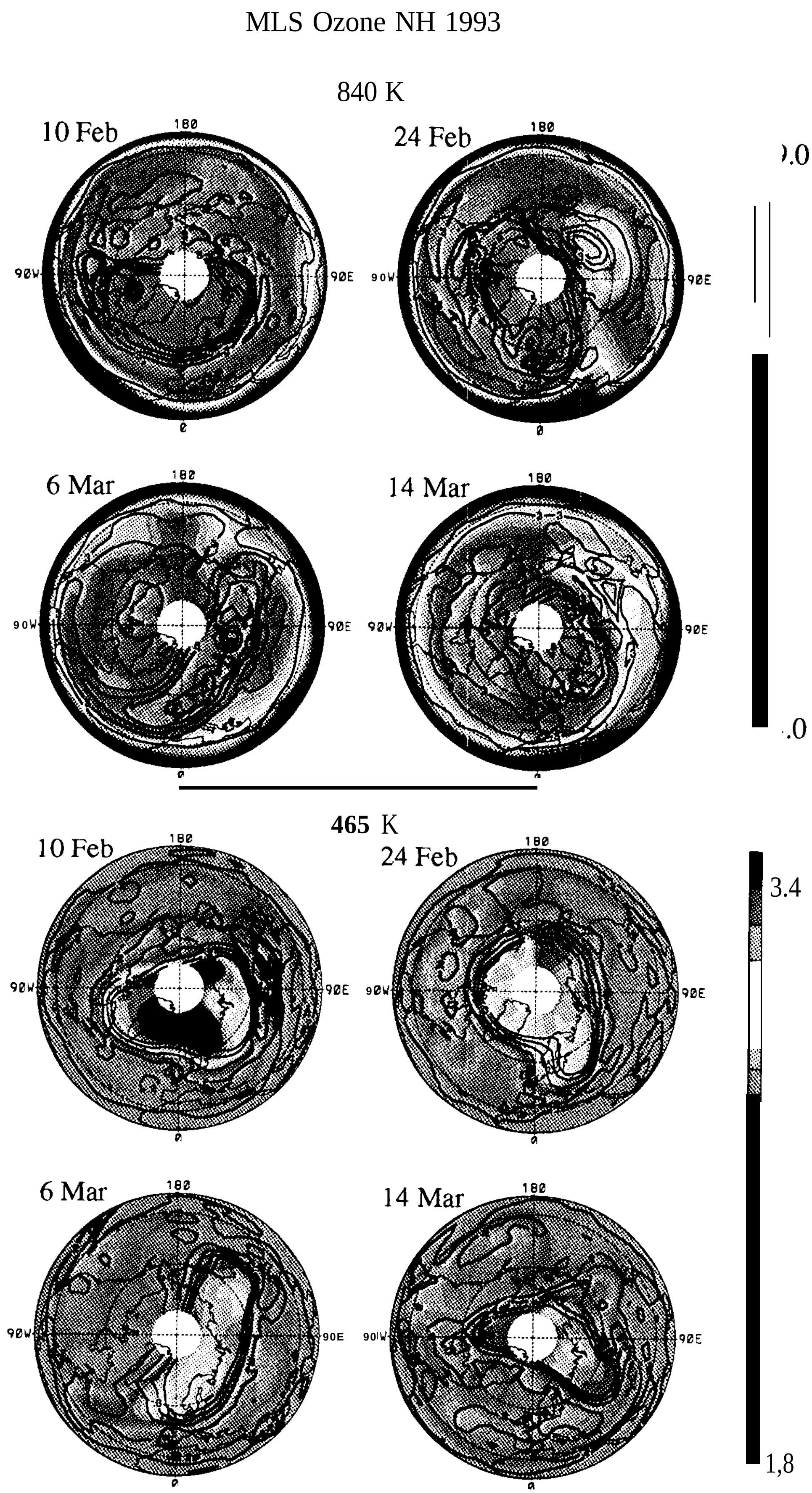

MLS Ozone NH 1993
840 K
10 Feb
24 Feb
6 Mar
14 Mar
180
90W
90E
0
465 K
10 Feb
24 Feb
6 Mar
14 Mar
3.4
1,8

Fig. 8

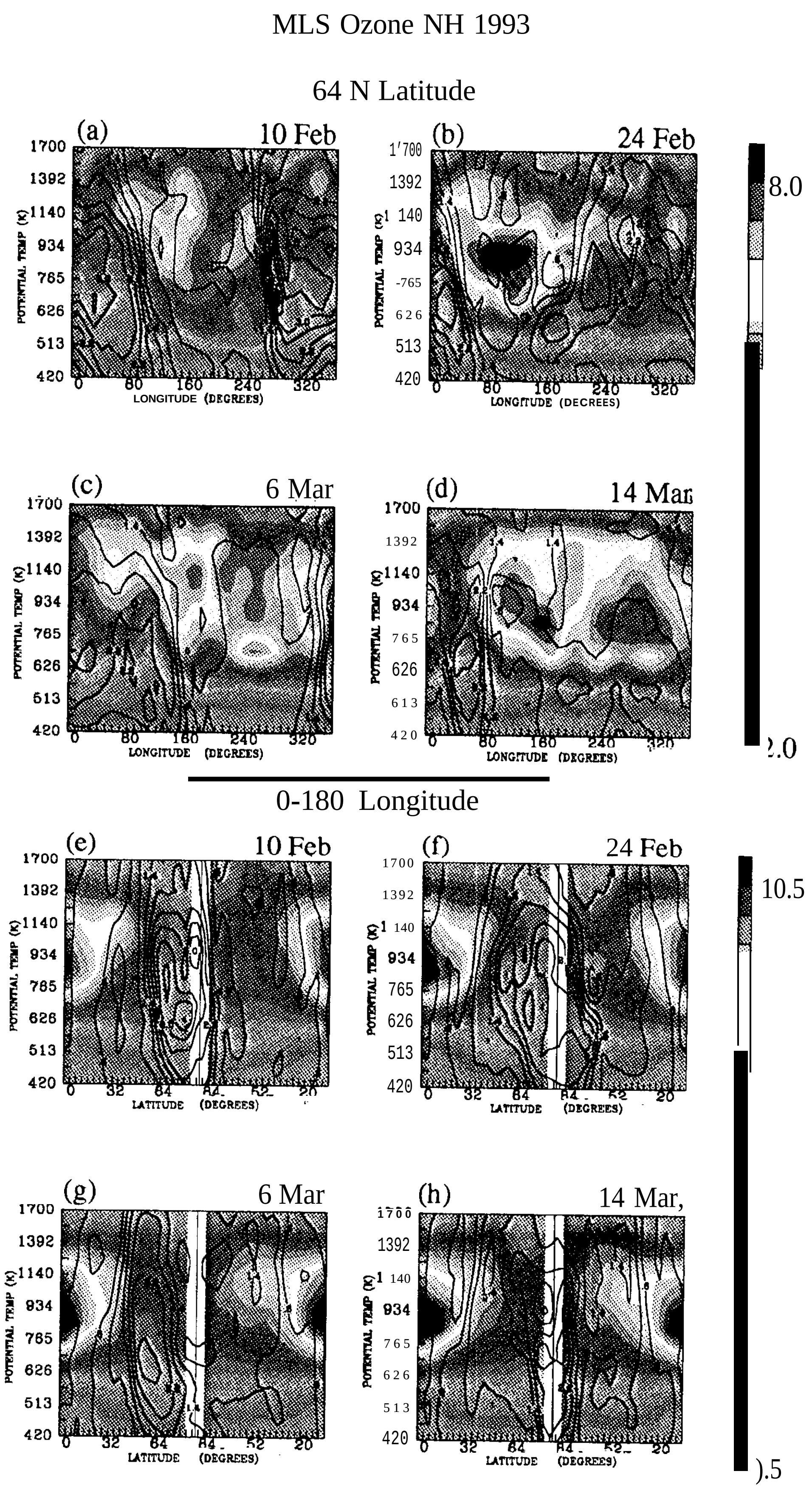

MLS Ozone NH 1993
64 N Latitude
(a) 10 Feb
(b) 24 Feb
(c) 6 Mar
(d) 14 Mar
POTENTIAL TEMP (K)
1700
1392
1140
934
765
626
513
420
LONGITUDE (DEGREES)
0 80 160 240 320
8.0
0-180 Longitude
(e) 10 Feb
(f) 24 Feb
(g) 6 Mar
(h) 14 Mar,
LATITUDE (DEGREES)
0 32 64
10.5
).5

Fig. 9

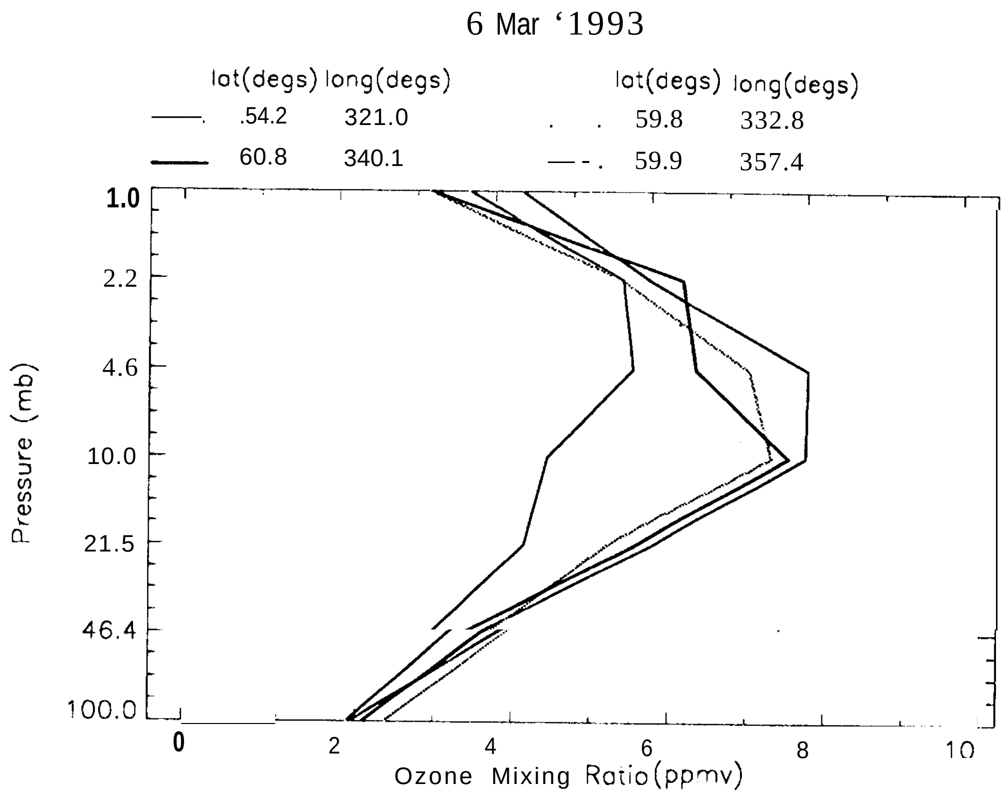

6 Mar '1993
lat(degs) long(degs)
.54.2 321.0
60.8 340.1
lat(degs) long(degs)
59.8 332.8
59.9 357.4
1.0
2.2
4.6
10.0
21.5
46.4
100.0
Pressure (mb)
0
2
4
6
8
10
Ozone Mixing Ratio(ppmv)

Fig. 10

MLS Ozone NH 1994

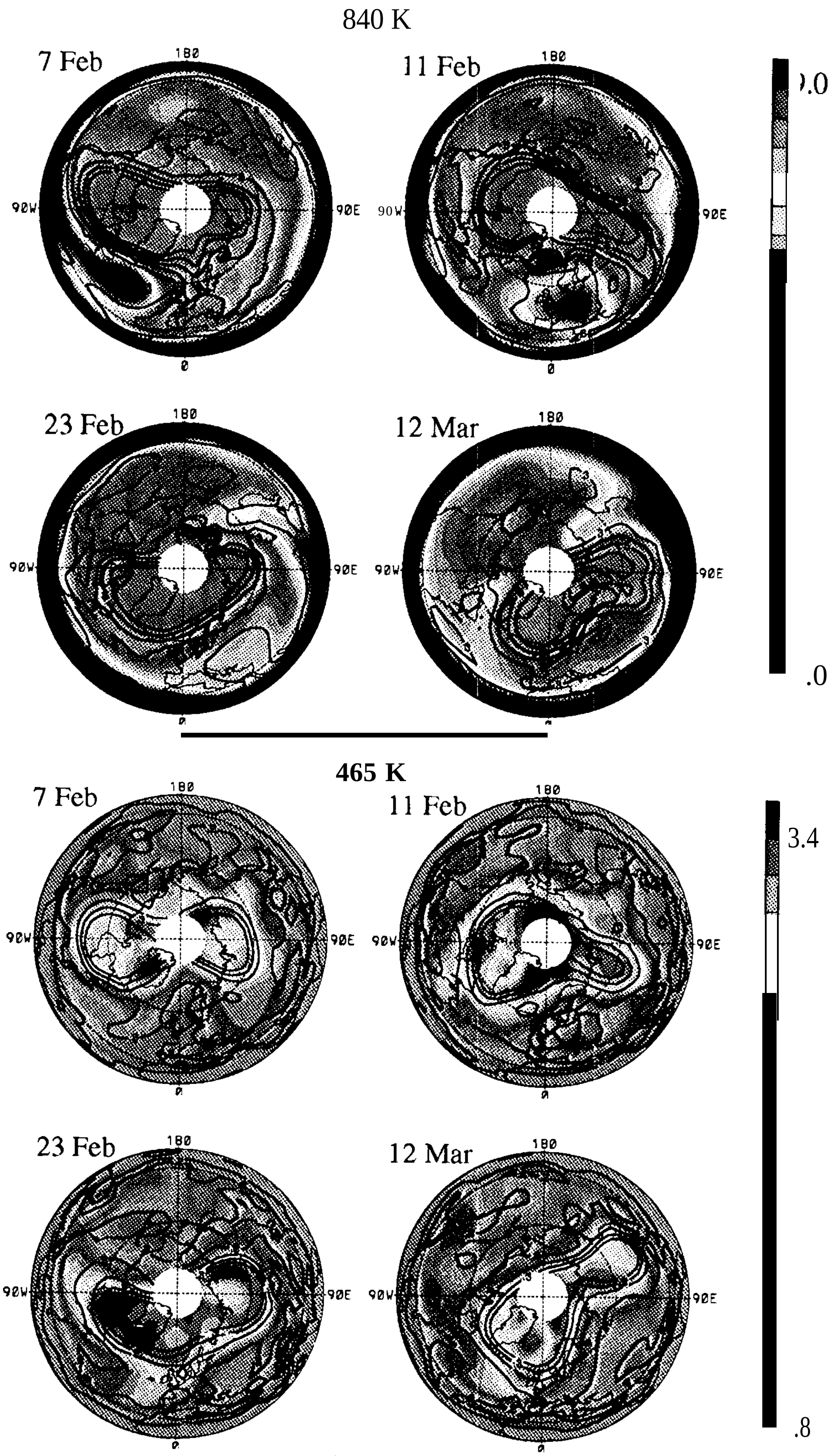
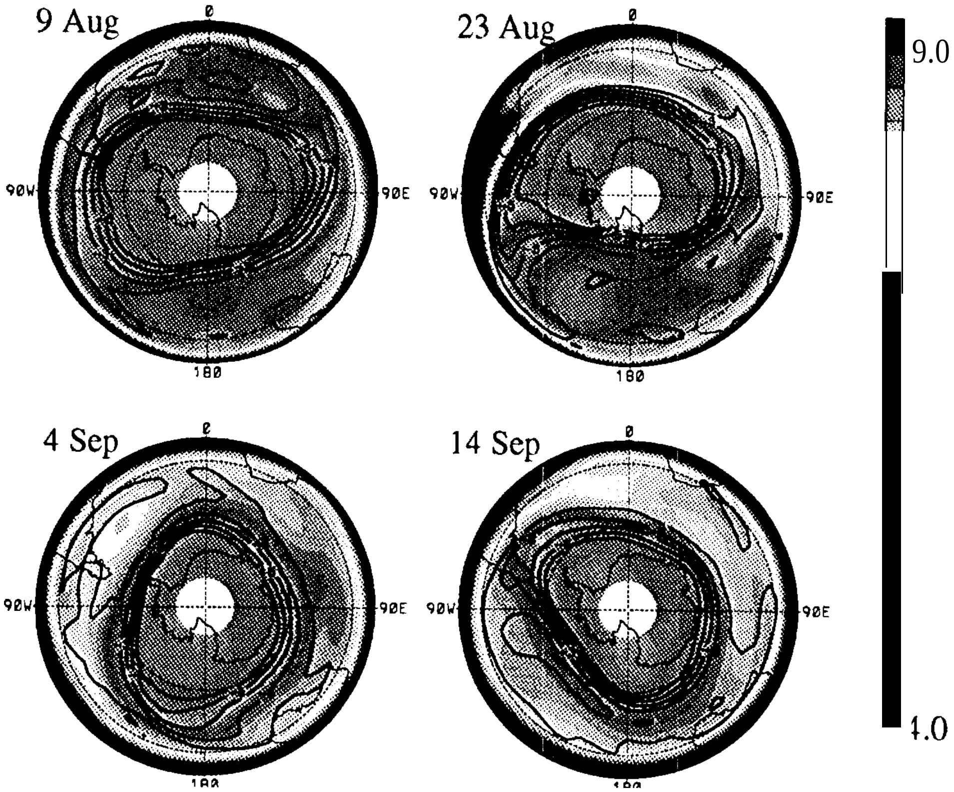


Fig. 11

MLS Ozone SH 1993

840 K



465 K

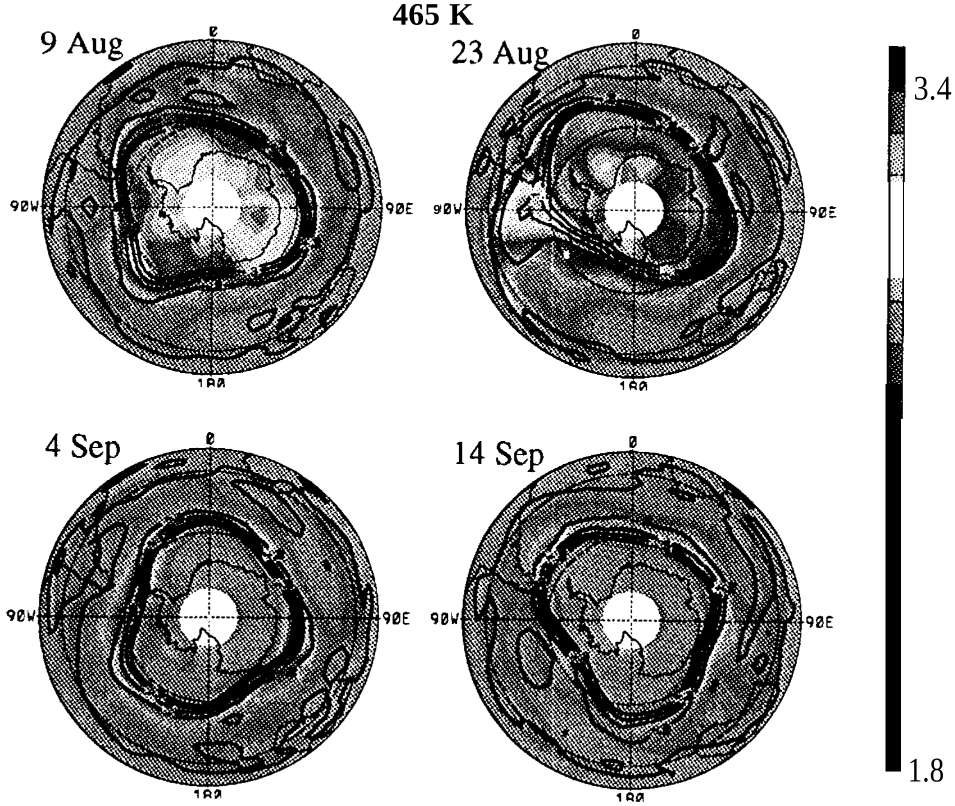
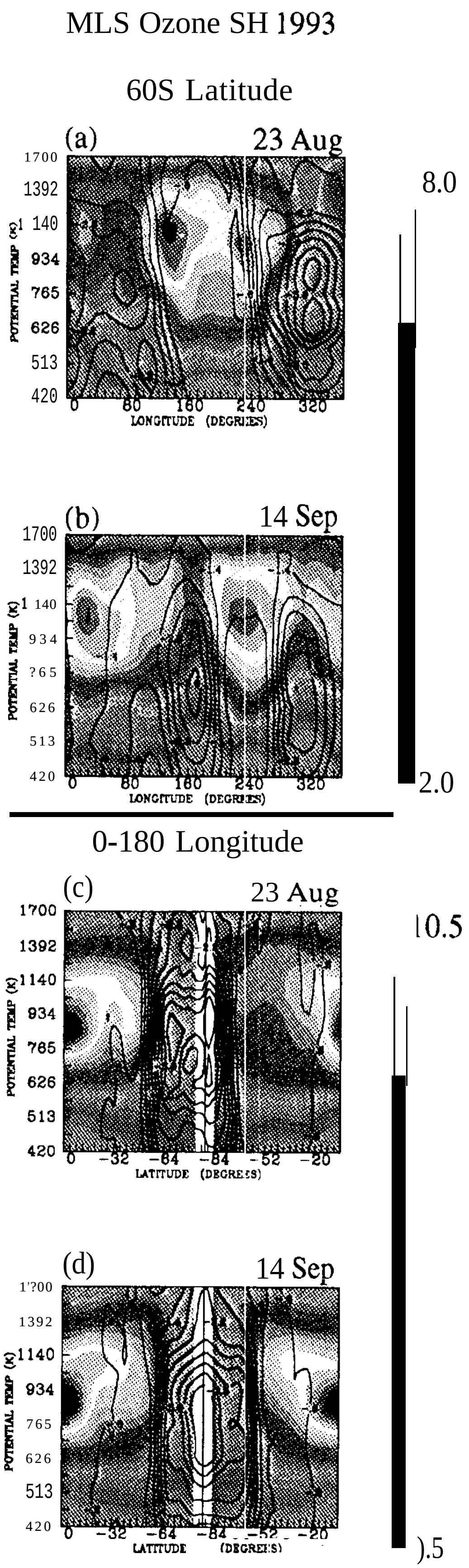


Fig. 12



MLS Ozone SH 1993
60S Latitude
(a)
23 Aug
1700
1392
1140
934
765
626
513
420
POTENTIAL TEMP (K)
0
80
160
240
320
LONGITUDE (DEGREES)
(b)
14 Sep
8.0
2.0
0-180 Longitude
(c)
23 Aug
LATITUDE (DEGREES)
-32
-64
-84
-52
-20
(d)
14 Sep
10.5

Fig. 13

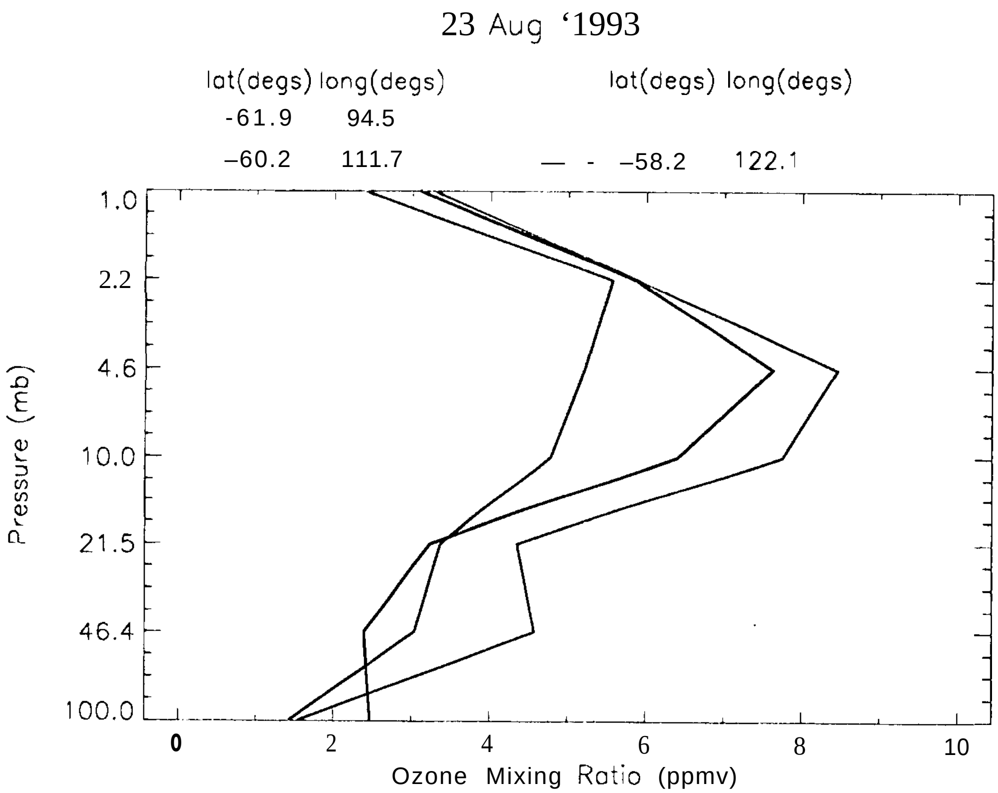

23 Aug '1993
lat(degs) long(degs)
-61.9 94.5
-60.2 111.7
lat(degs) long(degs)
-58.2 122.1
1.0
2.2
4.6
10.0
21.5
46.4
100.0
Pressure (mb)
0
2
4
6
8
10
Ozone Mixing Ratio (ppmv)

Fig. 14